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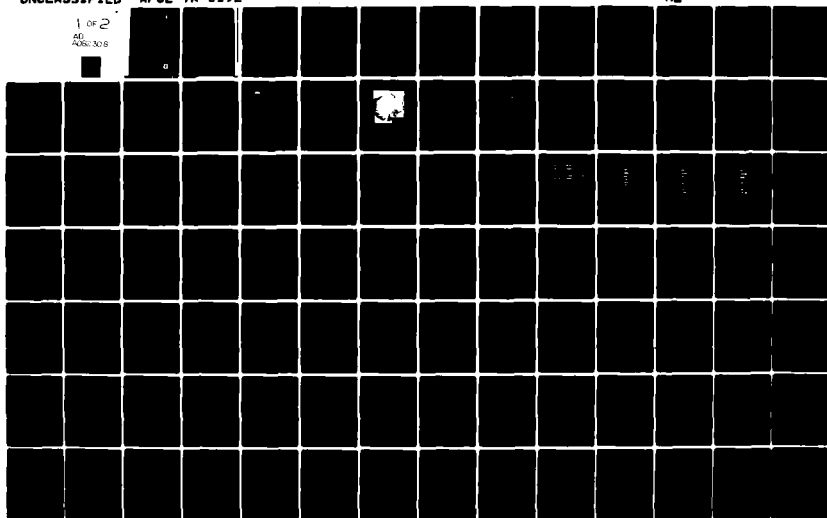
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**Proceedings of the Air Force  
Geophysics Laboratory Workshop on  
Geomagnetism: April 6-7, 1979**

**EDITORS:**

**R.C. SAGALYN  
R.O. HUTCHINSON  
S. GUSSENHOVEN**

**20 August 1979**

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**AIR FORCE SYSTEMS COMMAND, USAF**

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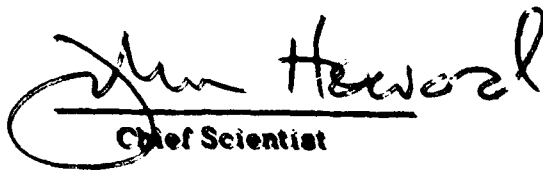
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FOR THE COMMANDER

  
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) On 6-7 April 1979 a two-day workshop on geomagnetism was held at the Air Force Geophysics Laboratory (AFGL). Proceedings of the workshop presented here include: (1) reports on tutorial sessions concerning magneto- spheric physics and geomagnetic pulsations, (2) summaries of contributed papers, (3) descriptions of active magnetometer networks, (4) conclusions of workshop-discussion groups. Special emphasis is given to the use and future potential of the AFGL midlatitude magnetometer chain.			

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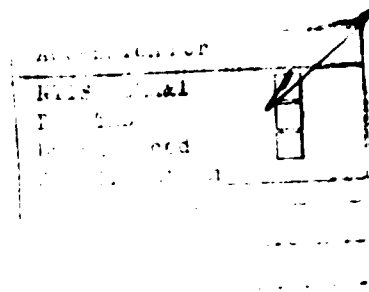
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A

## Preface

Geomagnetism as a science began with the concept put forth by Gilbert in the 16th century that the earth itself is a magnet. Secular variations were discovered in the seventeenth century. With the observations of transient variations of the field in the eighteenth century it was generally recognized that geomagnetism is a dynamic phenomenon. By the end of the 19th century a large number of magnetic observatories were established around the world. Through coordinated measurements from many stations, the worldwide nature of major disturbances was established. At the same time the greatly increased volume and precision of data made it clear that the phenomena being studied were very complex. Early in the 20th century, the intimate connection between solar and geomagnetic phenomena was ascertained from the correlation of recurrent disturbances with the 27 day solar rotation and later by the observed relation between magnetic storms and solar flares. The important fact that the geomagnetic field interacts with a continuous stream of solar plasma was established only during the last 20 years as a result of satellite observations. Today it is generally recognized that the geomagnetic field is a complex feature of the planet interacting with its environment in the solar system.

A workshop on geomagnetism was held at the Air Force Geophysics Laboratory on April 6-7, 1979 to (1) survey the present state of knowledge of the geomagnetic field during quiet and disturbed conditions; (2) obtain an overview of the work being carried out around the world both from the ground based networks and satellite observations; and (3) reach consensus in the informal workshops as to what analytical and experimental work needs to be done to make significant progress in our

understanding of geomagnetic variations, which will in turn contribute to our knowledge of magnetosphere, ionosphere, and geological processes. The two-day program consisted of tutorial lectures, brief contributed papers, descriptions of magnetometer networks, and discussion groups. Each session was assigned a reporter whose responsibility it was to summarize the session for the Proceedings. Each session forms a section in the Proceedings. A copy of the program is included as well. We readily acknowledge, as can be seen from the program, that the workshop was biased toward ground-based studies.

We hoped that by means of the Workshop the participants would become familiar with the AFGL Real Time Magnetometer chain and would be encouraged to use both the pulsation data and flux gate measurements from this network. David Knecht, with support from Charles Tsacoyeanes and Bob Hutchinson, was responsible for the network development. A report prepared by the above describing the network and data handling system is available for distribution. Paul Fougere is responsible for the scientific analysis and utilization of network data.

Bob Hutchinson, Dave Knecht, and Paul Fougere, all of AFGL, worked with me in planning and organizing the Workshop. I am deeply grateful for their energy, enthusiasm, and effectiveness in carrying out the many tasks it entailed. I would also like to thank Bob Hutchinson, Peter McNulty of Clarkson College, Bob Filz of AFGL, Pat Hagan of Emmanuel College, and Fred Rich of Regis College for handling various travel arrangements, the logistics of contractual efforts and other details of the Workshop. I would like to express our appreciation to the speakers for the quality of their presentations and to the reporters who did an excellent job in summarizing the results in a timely manner. Bob Hutchinson and Susan Gussenhoven acted very effectively as my co-editors in preparing the Proceedings and I am grateful for their assistance.

Work done in the Workshop was supported by Air Force Contracts F19628-77-C-0122 and F19628-79-C-0102.

We wish to thank all the participants for a very stimulating and rewarding meeting.

Rita C. Sagalyn

## Contents

WORKSHOP PROGRAM	11
I. TUTORIAL LECTURES	13
A. Magnetospheric Physics	14
1. Some Energy Principles and their Relationship to Magnetospheric Physics	14
2. Relationship to the AFGL Magnetometer Chain	24
B. Geomagnetic Pulsations	29
1. Introduction	29
2. Pulsation Theory	29
3. Ionospheric Effects	32
4. Global Extent	34
5. Pulsation Data Analysis Techniques	40
C. Applications	47
1. Introduction	47
2. Constituents of the Geomagnetic Field	47
3. Crustal Anomalies and the Search for New Natural Resources	48
4. Terrestrial Conductivity	49
5. Long Man-made Conductors	49
6. Relationship to the AFGL Magnetometer Chain	50
II. CONTRIBUTED PAPERS: BRIEF REPORTS	53
A. Geomagnetic Pulsations	54
B. Magnetospheric Physics	57
III. THE AFGL CHAIN: WORKSHOPS	59
A. Workshop on Magnetic Disturbances	60
B. Workshop on Geomagnetic Pulsations	63
1. The Organization and Presentation of the AFGL Network Data Set	63



## Contents

2. Specific Research Projects for which the AFGL Network Would be Useful	65
a. The Study of Pi2's	65
b. Solar Wind/Ground Correlations	65
c. Magnetosphere/Ground Correlations	65
d. E-W Variations of Pulsations	66
3. Special Events Studies and a Second Workshop	66
4. Participants Research Plans	67
C. Workshop on Applications	69
IV. NETWORKS	71
A. Air Force Geophysics Laboratory Network	72
B. Canadian Magnetic Observatory Network	76
C. Institute of Geological Sciences Network	84
D. U.S. - Canadian Network	90
E. Air Weather Service Network	95
F. Scandanavian IMS Network	96
G. University of Alberta Network	100
H. Alaskan Network	102
I. Indian Network	105
J. National Institute of Polar Research Network	107
K. United States Geological Survey Network	109
REFERENCES	111
APPENDIX A: A List of Potential Events for Special Study	113
APPENDIX B: Geomagnetic Field Workshop Questionnaire	115
APPENDIX C: Questionnaire Responses	117
LIST OF ATTENDEES	127

## Illustrations

1. Estimated Flux Return to the Sunward Magnetosphere During Expansion Events versus $\int ALdt$ Taken Over the Same Time Interval (Holzer and Slavin <sup>1</sup> )	16
2. A Block Diagram Illustrating How the Poynting Flux in the Solar Wind and Incident Upon the Magnetosphere is Dissipated Within the Magnetosphere (Courtesy of Akasofu)	17
3. Data from June 1974, Showing the AE Index (dashed line) and the Calculated Quantity $\epsilon = V_{sw} B^2 l^2 \sin^4 (\theta/2)$ (solid line) to Illustrate their Similar Variations in Time	17

## Illustrations

4. A Composite of DMSP Images Showing an Example of Auroral Emissions During a Substorm (Courtesy of Akasofu)	19
5. Time Development of a Substorm (Akasofu <sup>3</sup> )	20
6. Diagram of the Open Magnetosphere in Which the Solar Wind and Earth Magnetic Fields Merge (Courtesy of Kelley)	21
7. Qualitative Sketch of a Flux Transfer Event	22
8. Flux Eroded from the Forward Magnetosphere During an Interval of Contraction Shown as a Function of the Southward IMF Flux in GSM Coordinates	23
9. A Schematic Diagram of the Magnetospheric Volume in Which Energy from Joule Heating is Dissipated	23
10. Raw Telemetry Data from the Spacecraft Magnetometer, Electric Field Detector, Langmuir Probe and Planar Ion Probe During a Particularly Good Example of Intense Electric Fields at the Plasmapause	25
11. Ambient Electric Fields Converted into Flow Velocities and Plotted in Invariant Latitude Local Time Coordinate System (Smiddy et al <sup>6</sup> )	26
12. (a) The AU, AL Auroral Indices; (b) Five Superposed Mid-Latitude Magnetograms (Kakioka, Tashkent, Tangerang, San Juan, Honolulu); (c) The Eastward Component of the Equatorial Electric Field Measured at Jicamarca, Peru; (d) The Westward Component of the Auroral Electric Field Measured by Balloon Detectors at College, Alaska; (e) The Time Derivative of the Horizontal Component of the Magnetic Field at San Juan	27
13. Electric Field Data from Two Auroral Zones and One Equatorial Site Along with IMF and Auroral Activity Indices for 14 April 1978 (Kelley et al <sup>9</sup> )	28
14. Variation of the Resonant Period of the Fundamental Hydromagnetic Oscillation of a Single Magnetic Field Line as a Function of L-shell (Courtesy of J. Hughes)	31
15. The Amplitude of a Monochromatic Signal (from a Surface Wave in the Magnetosphere), in the Region of a Resonant Field Line as a Function of Latitude	31
16. Rotation of the Polarization Direction (by 90°) in Transmission of a Hydromagnetic Wave Through the Ionosphere (Courtesy of J. Hughes)	33
17. Field Variations (20-200 sec) for November 7-9, 1973, at SI and SA	36
18. Wave Ellipticities at SI and SA on November 8, 1973, Plotted at the Same Local Times (Barker et al <sup>10</sup> )	36
19. Data from South Uist (SU) and Pittsburgh (PB) for November 9, 1973	37
20. Data from South Uist (SU) and Pittsburgh (PB) for November 28, 1973	38
21. Data from South Uist (SU) and Pittsburgh (PB) for December 10, 1973	39

## Illustrations

22. H- and D-component Magnetometer Data from Girardville	41
23. Amplitude of the Magnetic Variations at the Peak of the Two Wave Events as a Function of Latitude (L.-value)	42
24. Magnetic Variations Recorded at Fort Providence in Northern Canada, December 3, 1977	44
25. Power Spectra of the Magnetic Variations shown in Figure 24 in the Measurement Coordinate System (Courtesy of Samson)	44
26. Power Spectra of the Magnetic Variations shown in Figure 24 in the Directions of Right and Left Hand Circularly Polarized Waves in the H-D Plane (Courtesy of Samson)	45
27. Power Spectra of the Magnetic Variations shown in Figure 24 Just North and South of a Resonance Region (Courtesy of Samson)	45
28. Geographical Locations of the AFGL Network Stations	73
29. Magnetic Observatories and Variation Stations of the Earth Physics Branch (Courtesy of Earth Physics Branch)	83
30. IGS Network Stations (Courtesy of IGS)	86
31. Quick Look Record Section (Courtesy of IGS)	87
32. Final Format Per Master Tape (Courtesy of IGS)	87
33. North American High-Latitude Magnetometer Network for IMS (Courtesy of NOAA)	92
34. North American Midlatitude Magnetometer Network for IMS (Courtesy of NOAA)	93
35. Midlatitude Chain H-Trace Day 81 (Courtesy of NOAA)	94
36. Scandanavian IMS Network (Courtesy W. Baumjohann)	97
37. IGM Magnetometer Chain Magnetograms X Component (Courtesy H. Maurer)	99
38. University of Alberta Magnetometer Array (Courtesy of University of Alberta)	101
39. IMS Alaska Meridian Chain (Courtesy of University of Alaska)	104
40. National Institute of Polar Research Magnetometer Array (Courtesy of NIPR Japan)	108

## Tables

1. Locations of the Data Collection Stations	73
2. Canadian Magnetic Observatory Network	79
3. Canadian Observatory Data Services and Costs	80
4. Temporary Magnetic Variation Stations	82
5. IGS Magnetometer Stations	83
6. IGS Data Tapes for Special Intervals	89
7. U.S. -Canadian IMS Magnetometer Network	94
8. Scandinavian IMS Network	98
9. University of Alberta Network	101
10. Alaskan Chain Stations	103
11. Indian Network	106
12. National Institute of Polar Research Network	108
13. United States Geological Survey Network	110

<p>FRIDAY MORNING Holzman Seminar Room</p>		<p>SATURDAY MORNING Holzman Seminar Room</p>	
8:45	Registration	9:00	Contributed Papers - M. Sugiura, Ch. J. Barfield, R. Carovillano, R. Wolf, M. Sugiura, P. Tanskanen, G. Siscoe, J. Feynmann, J. Walker, Others
9:00	Welcome B. S. Morgan, Col., AFGL Commander R. C. Sagalyn, Workshop Chairperson	10:45	Break
9:15	Tutorials - G. Siscoe, Ch. S.-I. Akasofu - Magnetic Storms R. McPherron - Satellite Measurements D. Southwood - Current Systems	11:00	Applications - J. Hermance, Ch. W. Campbell - Induced Currents on the Alaskan Pipeline J. Wood J. Hermance R. Regan
10:45	Break		
11:00	Networks D. Knecht - AFGL J. Walker - Dominion Observatory W. Stuart - ICS Edinburgh J. Joselyn - NOAA Others		
<p>FRIDAY AFTERNOON Holzman Seminar Room</p>		<p>SATURDAY AFTERNOON</p>	
1:30	Tutorials - E. Greenstadt, Ch. J. Hughes - Pulsation Theory J. Samson - Multivariate Analysis of U.F. L. Lanzerotti - Pulsation Measurements M. Kelly - Electric Field Measure- ments	1:30	Workshops (Concurrent Sessions) 1. Magnetic Disturbance (Seminar Room 2) Leader: J. Feynmann 2. Magnetic Pulsations (Holzman Seminar Room) Leader: L. Lanzerotti 3. Other Disciplines (PHG Seminar Room) Leader: W. Campbell Break 3:15 Workshop Summary - R. Carovillano, Ch.
3:15	Break		
3:30	Contributed Papers H. Fukunishi, E. Greenstadt, E. Maple, P. Fougere, A. Wolf, W. Bellew		

## Proceedings of the Air Force Geophysics Laboratory Workshop on Geomagnetism: April 6-7, 1979

### I. Tutorial Lectures

The tutorial presentations were divided into three classes.

The first class dealt with our present understanding of the magnetosphere and the potential for the AFGL magnetometer chain to contribute to further understanding. Tutorials were given by S. -I. Akasofu, R. McPherron, and D. Southwood.

The second class dealt with the theory and measurements of geomagnetic pulsations and data analysis techniques that bring the two more closely together by presenting the large amount of information obtained from spectral analysis concisely. Tutorials were given by J. Hughes, L.J. Lanzerotti, J. Samson, and M.C. Kelley.

The third dealt with applications that can be made from increased knowledge of the geomagnetic field and the variations. These included locations of natural resources, determining the earth's conductivity, and predicting effects on long conductors, such as pipelines. Tutorials were given by W.H. Campbell, J. Wood, J. Hermance, and R. Reagan.

Rather than discussing the individual talks, the recorders have attempted to present a coherent summary of these three general topics. The recorders were: M.C. Kelley, W. Bellew, J. Hughes, and R. Reagan.

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(Received for publication 10 August 1979)

## A. MAGNETOSPHERIC PHYSICS

(Reporter: M. Kelley)

### 1. Some Energy Principles and their Relationship to Magnetospheric Physics

Study of magnetospheric physics began with the observation of short period fluctuations of the earth's magnetic field. These were eventually shown to relate to auroral displays and solar activity. In the space age we have extended our data base to include in situ magnetosphere and interplanetary observations and we are now beginning to understand the complex relationship between  $\delta \bar{B}$  measured on the ground and the current systems which form the magnetospheric cavity. It should be noted at the outset that there are distinct limitations to magnetic field observations. First they respond to both "local" ionospheric currents and to distance current systems such as those at the magnetopause, in the ring current, and in the geomagnetic tail. Second, the extremely important field aligned currents and associated Pedersen currents are almost perfectly shielded from ground observations. Thus an inspired combination is needed of such parameters as ground magnetic fields, electric field patterns, field aligned current measurements from satellites, auroral imaging, interplanetary data, etc. It is thus not surprising that many outstanding problems remain in magnetospheric physics.

Although eventually detailed three dimensional models will be necessary to reproduce the complexity of the near space region of the earth, many of the principles can be understood from the energy theorem of electromagnetic theory. These results can also guide us in choosing key physical parameters for measurement and in building a conceptual model. The energy theorem derives from the stored magnetic energy in a system

$$W_B = \frac{1}{2\mu} \int B^2 dV \quad (1)$$

where  $dV$  is the volume element. We study changes of this quantity with time which can be written

$$\frac{\partial W_B}{\partial t} = \frac{1}{\mu} \int \bar{B} \cdot \frac{\partial \bar{B}}{\partial t} dV \quad (2)$$

Then using  $\partial \bar{B} / \partial t = \bar{\nabla} \times \bar{E}$ ,  $\bar{B} = \mu \bar{H}$  and the vector identity  $\bar{\nabla} \cdot (\bar{E} \times \bar{B}) = \bar{B} \cdot (\bar{\nabla} \times \bar{E}) - \bar{E} \cdot (\bar{\nabla} \times \bar{B})$  we have

$$\frac{\partial W_B}{\partial t} = - \int \bar{\nabla} \cdot (\bar{E} \times \bar{H}) dV = \int \bar{E} \cdot (\bar{\nabla} \times \bar{H}) dV \quad (3)$$

using  $\bar{J} = c(\bar{E} + \bar{V} \times \bar{B})$  and applying the divergence theorem to convert the first volume integral to a surface integral

$$\frac{\partial W_B}{\partial t} = \oint_{\Sigma} (\bar{E} \times \bar{H}) \cdot d\hat{s} = \int \left[ \left( \frac{\bar{J}}{c} - \bar{V} \times \bar{B} \right) \cdot \bar{J} \right] dV \quad (4)$$

and finally,

$$\frac{\partial W_B}{\partial t} = \oint_{\Sigma} (\bar{E} \times \bar{H}) \cdot d\hat{s} = \int \frac{J^2}{\sigma} dV = \int \bar{\nabla} \cdot (\bar{J} \times \bar{B}) dV \quad (5)$$

In words, the change in stored magnetic energy in a volume equals the energy flux in, minus the resistive energy loss, minus the mechanical work done against the  $\bar{J} \times \bar{B}$  force.

This shows that the energy input to the magnetosphere in the form of stored magnetic energy, Joule heat, and mechanical energy is related to the Poynting flux across the magnetopause. In a closed magnetosphere with the surface an equipotential, no energy could cross the surface ( $\bar{E}$  everywhere normal) and there could be no internal circulation (convection) and no storage of magnetic energy for later release (substorms). Two popular sources for a component of  $\bar{E}$  parallel to the magnetopause are viscous interaction and reconnection. Both of these processes result in a net component of  $\bar{E}$  parallel to the magnetopause and a net flow of energy into the magnetosphere.

A steady state magnetosphere could be defined as one in which no net magnetic field energy is being added or destroyed anywhere in the system. This can happen in a geometrically static magnetic field configuration in which magnetic flux eroded from or added to the front side is stored in or removed from the tail. Note that this does not mean a dynamically stable magnetosphere since the Poynting flux added can all appear as motions and  $\bar{J} \cdot \bar{E}$  dissipation in the system. Two examples of such effects are ionospheric currents and magnetospheric convection. Less obvious but equally important are energization of energetic particles as their  $\bar{E} \times \bar{B}$  drifts take them parallel to  $\bar{E}$  ( $\bar{J} \cdot \bar{E} \neq 0$ ) and acceleration of auroral particles along magnetic field lines when  $\bar{E} \cdot \bar{B} \neq 0$ . Note that the conventional wisdom is that the latter occurs when  $J_{11}$  exceeds some limit (when the ionosphere cannot cope with



the full  $\bar{\mathbf{J}} \cdot \bar{\mathbf{E}}$  requirement) and results in finite electric fields parallel to  $\bar{\mathbf{B}}$  and a finite  $\bar{\mathbf{J}} \cdot \bar{\mathbf{E}} > 0$  along  $\mathbf{B}$ .

At present it is very difficult to add up all these energy sinks even if we knew when the magnetospheric geometry was static. There are times when we know the system is relaxing from some disturbed state, however, and we might hypothesize that no major input of energy is taking place. Holzer and Slavin<sup>1</sup> have studied such cases by using data from outward bound satellites which have detected multiple magnetopause crossings as it expands outward. The system is thus approaching a lower energy state since the dipole field which extends to infinity is the ground state for the magnetosphere. The magnetic flux  $\Phi_r$  added to the front side is plotted versus the integrated auroral zone magnetic disturbance for nine cases in Figure 1. A linear relationship is indicated which suggests that the energy released in the reconfiguration of the magnetosphere is proportional to the integrated auroral index. By Eq. (5) the energy appears as  $\bar{\mathbf{J}} \cdot \bar{\mathbf{E}}$  dissipation in the magnetosphere or ionosphere, plus convection. Note that Eq. (5) shows that the inner magnetospheric convection is driven by the magnetic flux storage in the distorted magnetosphere. This reconfiguration would presumably continue until a dipole field was reestablished if no new Poynting flux entered the system. A block diagram of this system is given in Figure 2.<sup>2</sup>

Evidence for the importance of this Poynting flux is presented in Figure 3. The parameter (see also Figure 2)

1. Holzer, R. E. and Slavin, J. A. (1978) Magnetic flux transfer associated with expansions and contractions of the dayside, *J. Geophys. Res.* 83:3831.
2. Akasofu, S.-I. (1979) Interplanetary energy flux associated with magnetospheric substorms, *Planet. Sp. Sci.* 27:425.

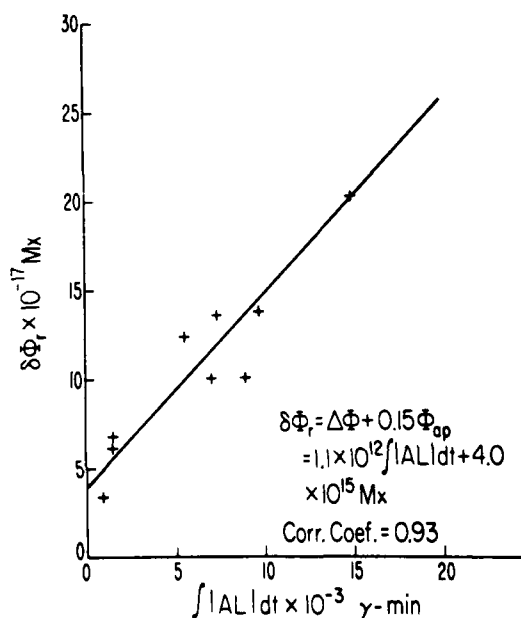


Figure 1. Estimated Flux Return to the Sunward Magnetosphere During Expansion Events versus  $\int ALdt$  Taken Over the Same Time Interval (Holzer and Slavin<sup>1</sup>)

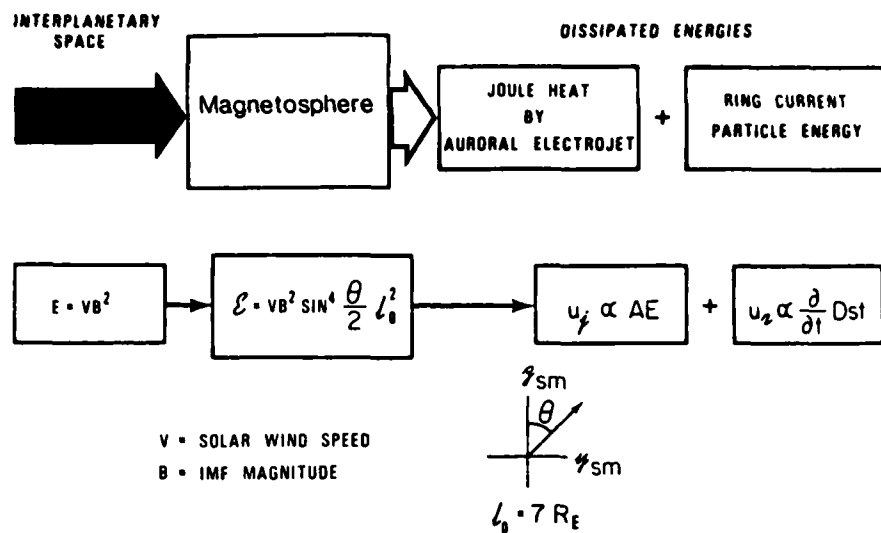


Figure 2. A Block Diagram Illustrating How the Poynting Flux in the Solar Wind and Incident Upon the Magnetosphere is Dissipated Within the Magnetosphere (Courtesy of Akasofu)

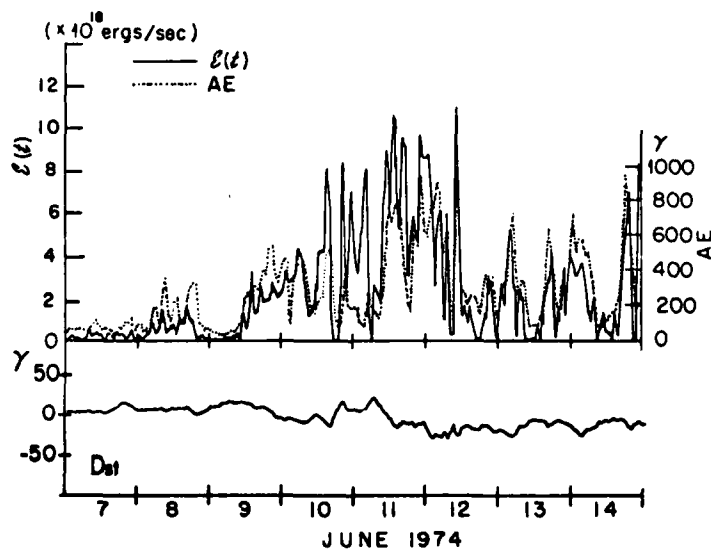


Figure 3. Data from June 1974, Showing the AE Index (dashed line) and the Calculated Quantity  $\epsilon = V_{sw} B^2 l_0^2 \sin^4 (\theta/2)$  (solid line) to Illustrate Their Similar Variations in Time. The lower panel gives  $D_{st}$  for the same time interval (Akasofu<sup>2</sup>)

$$\epsilon = V_{SW} B^2 t^2 \sin^4 (\theta/2) \quad (6)$$

where  $V_{SW}$  is the solar wind speed,  $B^2$  is the interplanetary field (IMF),  $\theta$  is the angle between the meridional component of the IMF and the dipole field, and  $t^2$  the reconnection area, is plotted along with the auroral index AE. This parameter is basically the Poynting flux incident on the magnetosphere times an area related to the reconnection region. The excellent correlation suggests that the Poynting flux entering the magnetosphere drives the full spectrum of magnetospheric processes. Measurement of this parameter could thus be used to predict auroral substorms. The incident flux is apparently stored in the magnetospheric tail as magnetic energy,  $W_B$ , for a time and then explosively released during substorms. The manifestations of such a release results in intense current systems, energization of particles to high energy, and enhanced convection in the magnetosphere, all of which are represented in Eq. (5). An example of auroral emissions recorded by a DMSP satellite during a substorm are presented in Figure 4. The classical substorm picture first presented by Akasofu<sup>3</sup> as reproduced in Figure 5, was based on all-sky camera coverage. This concept has been verified and expanded by this satellite imaging technique.

Although considerable evidence exists for "reconnection" as the main source of energy input to the magnetosphere, definitive observations of a Dungey type merging process at the nose of the magnetosphere, as shown schematically in Figure 6, has eluded experimenters. Recent ISEE A/B observations by Russell and Elphic<sup>4</sup> suggest strongly that the process occurs in limited bundles of flux tubes as shown schematically in Figure 7. They observed such bundles of flux field with hot particles moving away from the sub-solar point at high velocity.

A test of these ideas is offered by Holzer and Slavin<sup>5</sup> in an extension of the study discussed earlier. They also studied times of inward magnetopause motion and argued as follows. The energy input to the magnetosphere must equal that eroded at the front plus that dissipated in the ionosphere. From the results shown in Figure 1 they converted the AL index to the equivalent net flux returned to the front side by inner magnetosphere convection, added this to the observed flux erosion, and plotted the result versus net magnetic flux applied to the magnetosphere,  $\Phi_{AP} = V_{SW}(B^2 \mu_0)A$ , where  $A$  is the projected area of the magnetosphere.

3. Akasofu, S.-I. (1954) The development of the auroral substorm, Planet. Space Sci. 12:273.
4. Russell, C.T. and Elphic, R.C. (1979) ISEE observations of flux transfer events at the dayside magnetopause, Geophys. Res. Lett. 6:33.
5. Holzer, R.E. and Slavin, J.A. (1978) A correlative study of magnetic flux transfer in the magnetosphere, J. Geophys. Res. 84:2573.



Figure 4. A Composite of DMSP Images Showing an Example of Auroral Emissions During a Substorm (Courtesy of Akasofu)

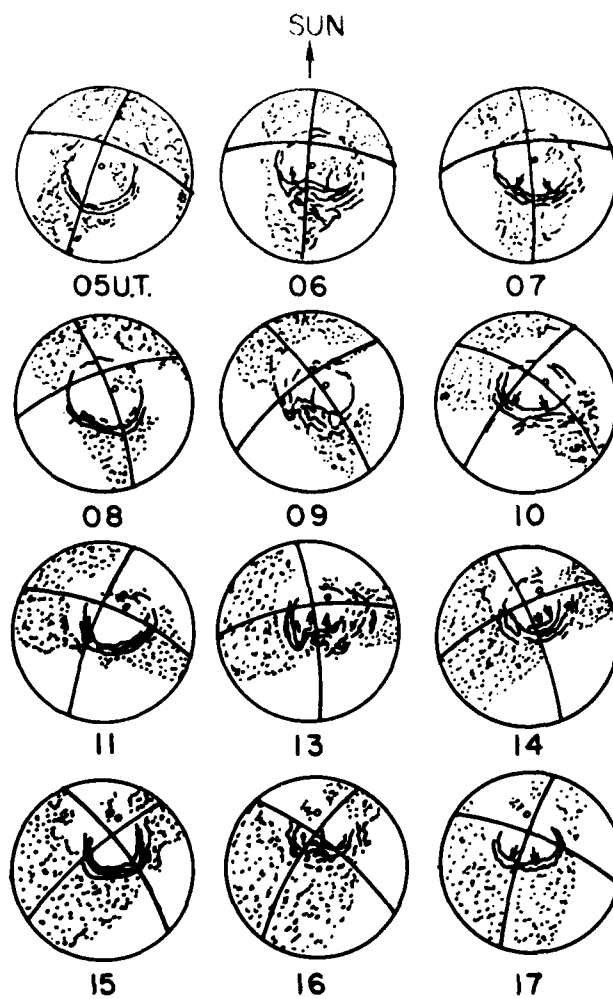


Figure 5. Time Development of a Substorm (Akasofu<sup>3</sup>)

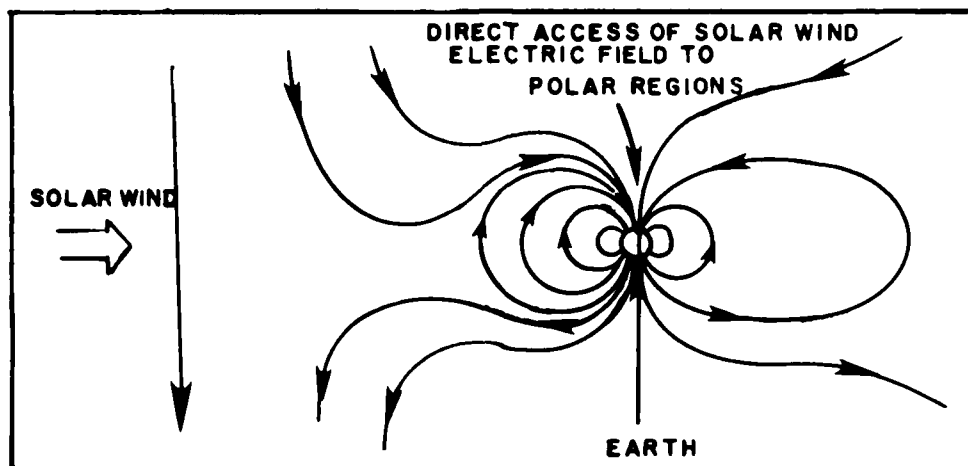


Figure 6. Diagram of the Open Magnetosphere in Which the Solar Wind and Earth Magnetic Fields Merge (Courtesy of Kelley)

Note that this applied flux is also proportional to the Poynting flux in the solar wind since  $\vec{E} \times \vec{B} / \mu_0 = (-\vec{V} \times \vec{B}) \times \vec{B} / \mu_0 = V B^2 / \mu_0$ . Although scattered, a linear relationship is indicated as shown in Figure 8.

This result suggests that during active times, 10 percent of the incident Poynting flux in the solar wind is input to the magnetosphere. It is interesting to note that the percentage is also roughly the same percentage of the total solar wind potential difference,  $V_T$ , which appears across the magnetosphere. That is  $V_T = E_{SW} \times 20 R_E = 10^{-3} \text{ mV/m} \times 8 \times 10^8 \text{ m} = 800 \text{ keV}$ , whereas the typical polar cap potential is 50-100 keV.

The importance of this cross polar cap potential coupled with the field aligned current patterns is clear from the following argument. Consider the vector identity

$$\vec{\nabla} \cdot (\vec{J} \phi) = \phi \vec{\nabla} \cdot \vec{J} + \vec{\nabla} \phi \cdot \vec{J} \quad (7)$$

with  $\vec{J}$  the current and  $\phi$  the potential. In a steady state  $\vec{\nabla} \cdot \vec{J} = \partial \rho / \partial t = 0$  and we have

$$\vec{E} \cdot \vec{J} = -\vec{\nabla} \phi \cdot \vec{J} = -\vec{\nabla} \cdot (\vec{J} \phi) \quad (8)$$

If we consider any closed surface and apply the divergence theorem, to Eq. (8) the total  $\vec{J} \cdot \vec{E}$  energy dissipated inside the volume equals the surface integral of  $-\vec{J} \phi$ , that is

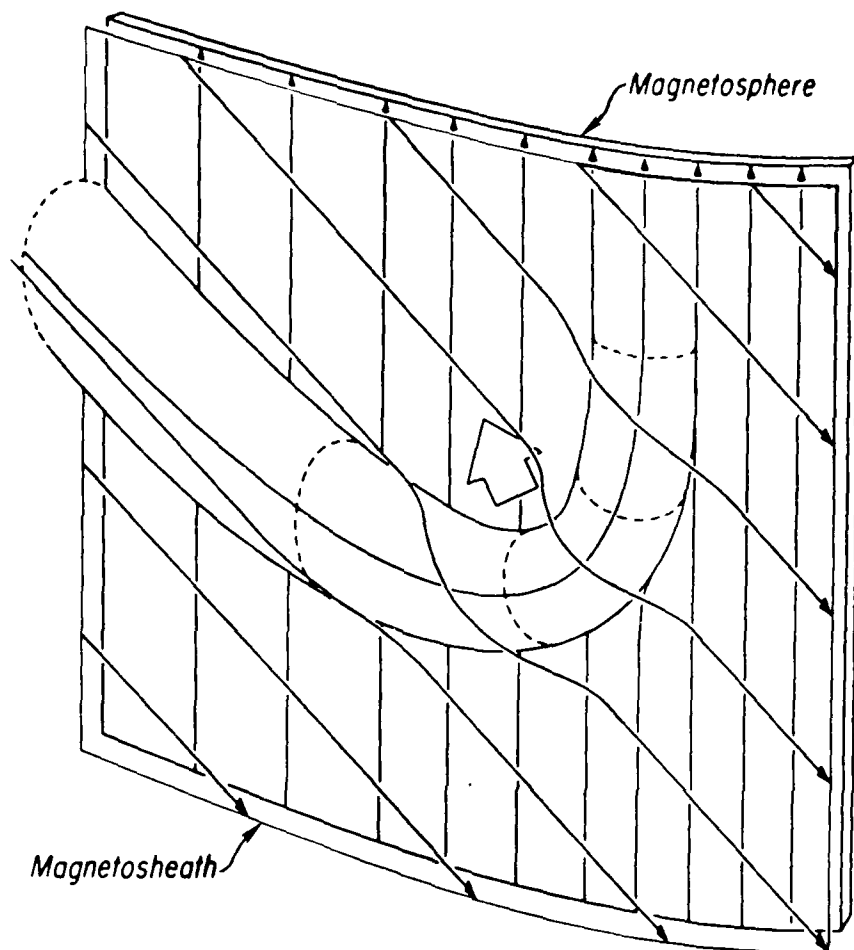


Figure 7. Qualitative Sketch of a Flux Transfer Event. Magnetosheath field lines (slanted arrows) have connected with magnetospheric field lines (vertical arrows) possibly off the lower edge of the figure. As the connected flux tube is carried by the magnetosheath flow in the direction of the large arrow, the stressed field condition at the "bend" tends to relax, effectively shortening the flux tube and straightening the bend. Magnetosheath field lines not connected to the magnetosphere drape over the connected flux tube and are swept up by its motion relative to the magnetosheath flow (Russell and Elphic<sup>4</sup>)

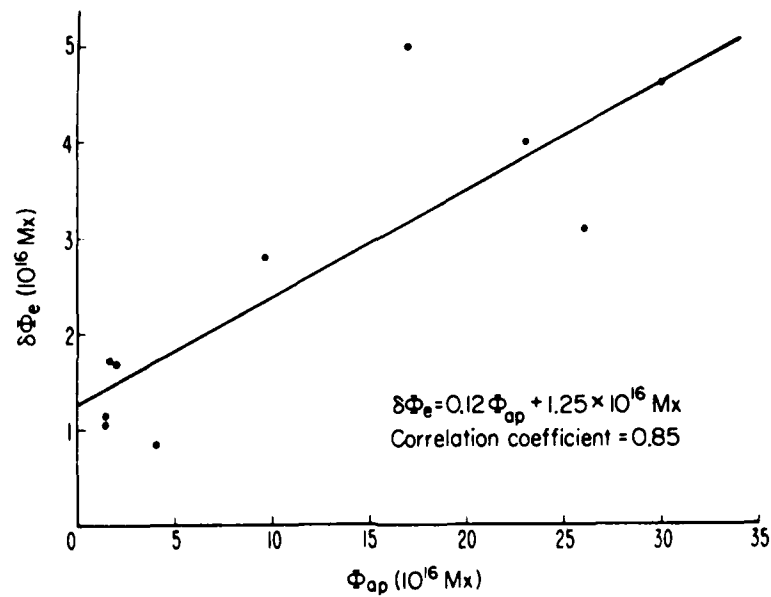


Figure 8. Flux Eroded from the Forward Magnetosphere During an Interval of Contraction Shown as a Function of the Southward IMF Flux in GSM Coordinates. Correction for returned flux is applied (Holzer and Slavin<sup>5</sup>)

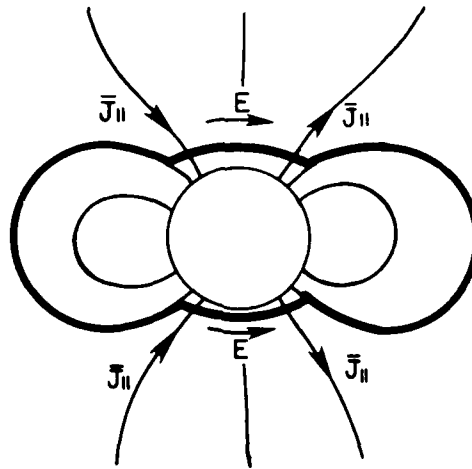


Figure 9. A Schematic Diagram of the Magnetospheric Volume in Which Energy from Joule Heating is Dissipated. The volume is generated by rotating the heavy line about the dipole axis (Courtesy of Kelley)



$$\int_V (\vec{E} \cdot \vec{J}) dV = \oint_{\Sigma} \phi \vec{J} \cdot \vec{n} ds$$

Viewing Figure 9 we choose the surface to be toroidal in shape defined by the closed magnetic field lines separating regions of oppositely directed  $J_{\parallel}$  with "caps" on both polar caps just above the polar ionosphere. In the figure, the dark line should be rotated about the dipole axis to generate the surface.

It is clear that if there are no radially inward magnetospheric currents across the L shell, the total energy input to the inner magnetosphere and ionosphere is determined by the field aligned currents and the cross polar cap potential. Ultimately this energy in turn drives all of the phenomena we know as auroral and magnetospheric physics including disturbed neutral atmospheric winds and composition, auroral emissions, current systems, the ring current, and the Van Allen radiation belts.

## 2. Relationship to the AFGL Magnetometer Chain

The AFGL chain is a mid-latitude system and hence cannot directly be used to study the energy input. Rather, it must be used to study the mechanisms occurring in the inner magnetosphere which dissipate some of this energy. Two important electrical processes of this type were discussed which could greatly benefit from the magnetic field data available in the AFGL chain.

One process is illustrated in Figure 10 which shows raw data from the AFGL electric field experiment on the S3-2 satellite. The sinusoidal signal in panel 2 is briefly interrupted by a localized intense electric field located at the transition between an  $H^+$  and  $O^+$  ionosphere (see the lower panel in which the ion current to a plasma sensor is plotted - large ratios of ram to wake ion current imply heavy  $O^+$  ions). This large field was located at  $L \approx 4$  and exceeded  $240 \text{ mV/m}$ . The total potential drop was about  $25 \text{ keV}$  across about  $1^\circ$  of latitude. The flow velocity is plotted in Figure 11 for this data and another similar event the next day.

It has been conjectured by Smiddy et al<sup>6</sup> that such fields are generated in response to magnetospheric currents due to the pressure gradients associated with hot plasma injection in substorms. Poleward fields rapidly can convect this

6. Smiddy, M., Kelley, M., Burke, W., Rich, F., Sagalyn, R., Shuman, B., Hays, R., and Lai, S. (1977) Intense poleward directed electric fields near the ionospheric projection of the plasmapause, Geophys. Res. Lett. 11:543.

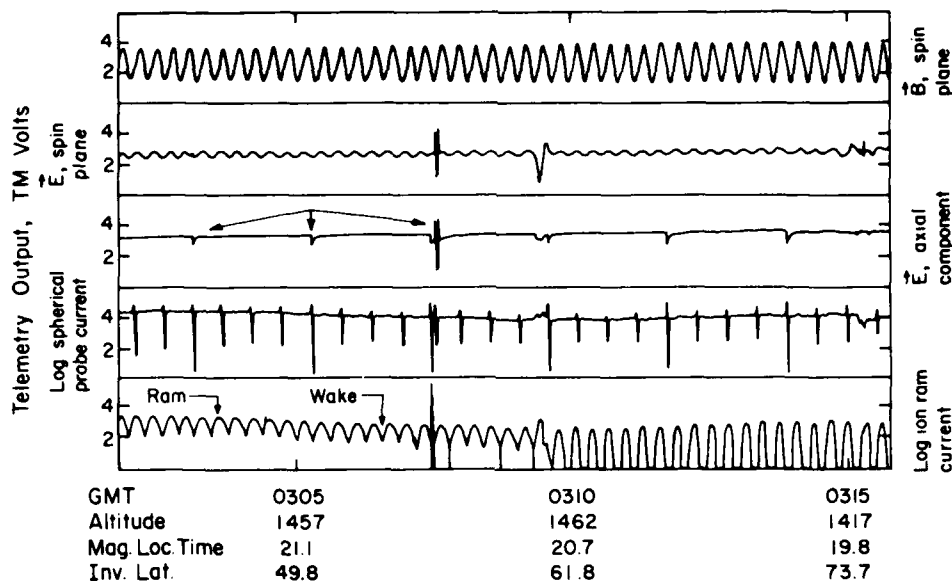


Figure 10. Raw Telemetry Data from the Spacecraft Magnetometer, Electric Field Detector, Langmuir Probe and Planar Ion Probe during a Particularly Good Example of Intense Electric Fields at the Plasmopause. Arrows in panel 3 show perturbation due to a calibration sequence (Smiddy et al<sup>6</sup>)

plasma around the earth and thereby ease the pressure gradient. Banks and Yasuhara<sup>7</sup> have suggested that a feedback mechanism exists to modify the ionosphere current even in the absence of precipitation. A suggested set of experiments to study this process include the AFGL chain, Millstone Hill, Roberval complex, AFGL airplane, and the Ithaca auroral radar.

A second exciting area of research involves electrical coupling between high and low latitudes. An example from Gonzales et al<sup>8</sup> is plotted in Figure 12. This shows a perturbed zonal electric field at Jicamarca in conjunction with a strikingly similar zonal perturbation at Chatanika during substorm activity. The lower plot displays the time derivative of the horizontal magnetometer signal ( $dB_H/dt$ ) at

7. Banks, P.M. and Yasuhara, F. (1978) Electric fields and conductivity in the nighttime E region: A new magnetosphere-ionosphere-atmosphere coupling effect, *Geophys. Res. Lett.* 12:1047.

8. Gonzales, C.A., Kelley, M.C., Fejer, B., Vikrey, J., and Woodman, R. (1979) Electric field coupling between high and low latitudes, *J. Geophys. Res.* (submitted for publication).

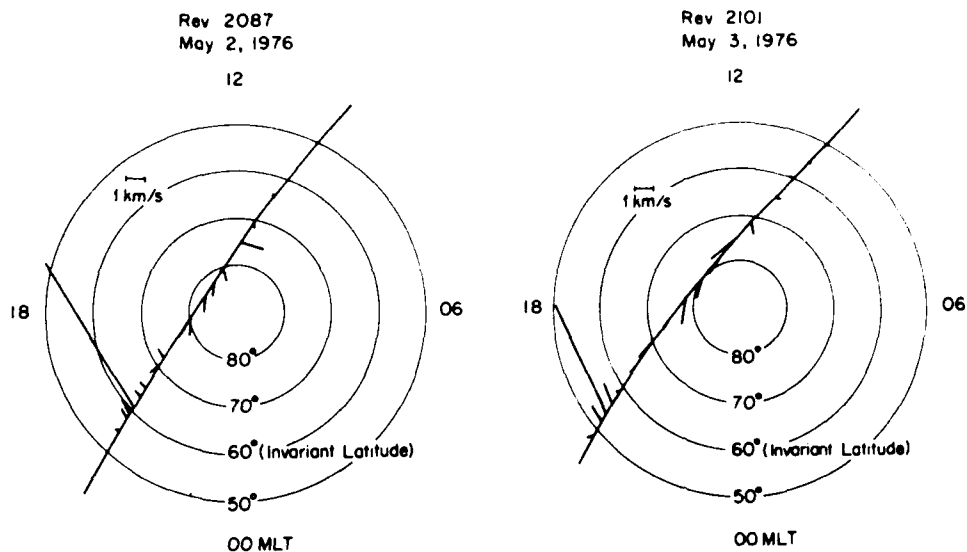


Figure 11. Ambient Electric Fields Converted into Flow Velocities and Plotted in Invariant Latitude Local Time Coordinate System (Smiddy et al<sup>6</sup>)

at San Juan which also has the same waveform. A different type of coupling is shown in Figure 13. Here a rotation of the interplanetary magnetic field from south to north (shaded times) seems to cause a rapid decrease in auroral convection and a simultaneous perturbation at Jicamarca. These phenomena could be studied using the same set of experiments although Millstone Hill would also have to be oriented southward half of the time. Attempts to correlate with Arecibo and Jicamarca would be very desirable.

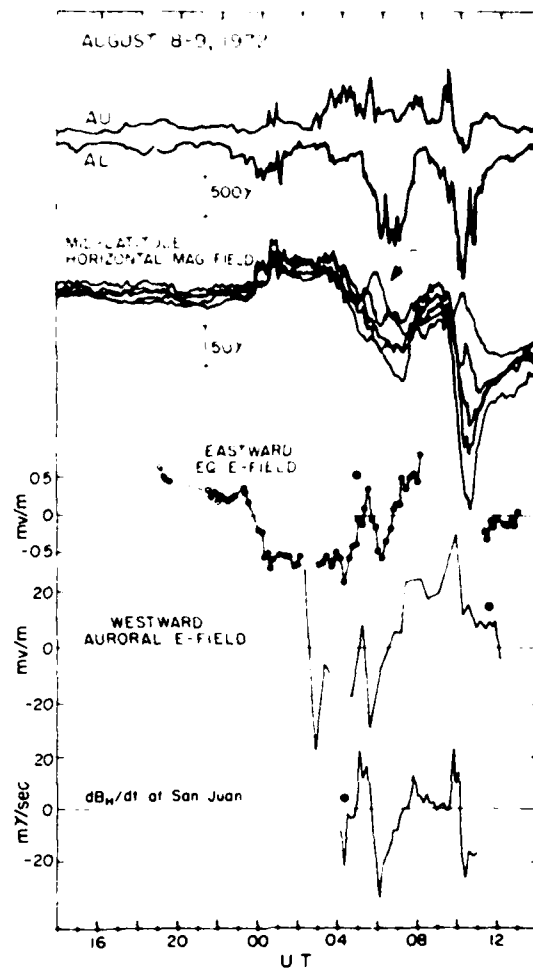


Figure 12. (a) The AU, AL Auroral Indices; (b) Five Superposed Midlatitude Magnetograms (Kakioka, Tashkent, Tangerang, San Juan, Honolulu); (c) The Eastward Component of the Equatorial Electric Field Measured at Jicamarca, Peru; (d) The Westward Component of the Auroral Electric Field Measured by Balloon Detectors at College, Alaska; (e) The Time Derivative of the Horizontal Component of the Magnetic Field at San Juan. Only for this case, the quiet behavior has been subtracted from the midlatitude magnetograms. The arrow in (b) points to the San Juan magnetogram. The dots indicate local magnetic midnight (Gonzales et al<sup>8</sup>)

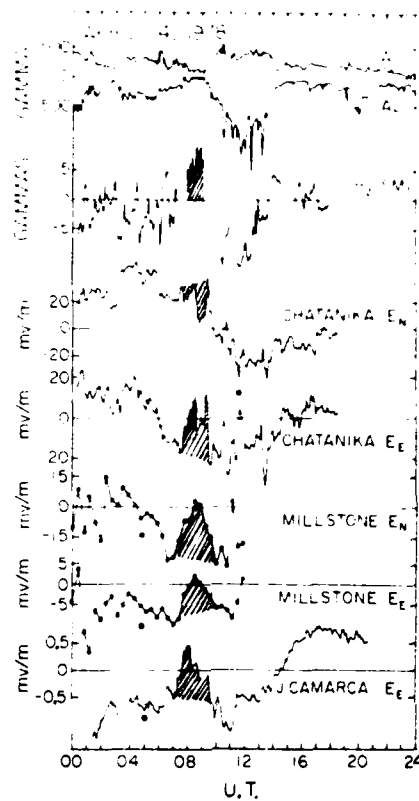


Figure 13. Electric Field Data from Two Auroral Zone and One Equatorial Site Along with IMF and Auroral Activity Indices for 14 April 1978 (Kelley et al.<sup>9</sup>)

9. Kelley, M.C., Fejer, B.G., and Gonzales, C.A. (1979) An explanation for anomalous equatorial ionospheric electric fields associated with a northward turning of the interplanetary magnetic field, Geophys. Res. Lett. 6:301.

## B. GEOMAGNETIC PULSATIONS

(Reporters: J. Hughes and W. Bellew)

### 1. Introduction

Geomagnetic pulsations are hydromagnetic waves whose periodic nature is caused by standing resonances of geomagnetic field lines in the earth's magnetosphere. While the propagation of such signals is reasonably well understood we still need to investigate how these waves are generated. There are many possible mechanisms most of which have a developed theory to explain them, thus experimental research is now required to distinguish between them. We also need to study the global variation of pulsation signals if pulsations are to be developed as a useful monitor of the near-earth space environment. Lanzerotti in the second tutorial showed how the Air Force chain, particularly when used in conjunction with data from other sources, can be used to study both these problems very effectively.

Geomagnetic pulsation research is a field where theory and experiment do interact closely, advances in one have led to successes in the other and vice versa. The new analysis techniques described by Samson in the third of these tutorials will help bring theory and experiment even closer together and will undoubtedly be used extensively in the future. More detailed accounts of these tutorials follow.

### 2. Pulsation Theory

It is generally agreed that pulsations are a manifestation of hydromagnetic waves (Alfvén waves) in the magnetosphere, and that field line resonance plays an important role in producing periodic signals. However, important questions remain to be answered: How are the waves produced, that is, where does the energy come from; how does this energy in the form of hydromagnetic waves propagate within the magnetospheric cavity as well as into it (from the magnetosheath) and out of it (to the ground); and finally, what is the sink of this energy, or how are the waves damped?

Pulsations can be produced either external or internal to the magnetosphere. Examples of sources external to the magnetosphere are the surface waves generated on the magnetopause by the Kelvin-Helmholtz instability, and waves produced at the bow shock or in the magnetosheath or cleft regions which subsequently propagate into the magnetosphere. Waves can also be produced inside the magnetosphere. These internal sources include plasma instabilities which fall into two classes. Microinstabilities are the result of unstable spatial gradients in the plasma and

produce a class of waves known as drift waves. Microinstabilities on the other hand, are caused by unstable plasma distributions in velocity space. These generally result in resonant wave-particle interactions which feed energy into the wave. Magnetospheric transients are another form of internal source. Information about a change in field configuration must travel in a plasma as a hydromagnetic wave. Pi2 pulsations are the result of the sudden changes in convection associated with a substorm. Examples of pulsations produced by all the methods mentioned here have been found and theories exist to explain most of them. What we need to know is which are the dominant methods and can we learn to easily distinguish waves produced by the various methods. We might expect that different types of pulsation are produced by different methods, but so far there is little evidence to either support or contradict this, except for certain very specific types of pulsation (for example, pc1's produced by ion gyroresonance).

In a uniform cold plasma there are two hydromagnetic wave modes: the fast (isotropic) mode,  $\omega^2 = k^2 V_A^2$ ; and the transverse (guided, Alfvén) mode,  $\omega^2 = k_{\parallel}^2 V_A^2$ . Here  $V_A$  is the Alfvén speed given by  $V_A^2 = B^2 / \mu_0 \rho$ ;  $\rho$  is the mass density and  $\mu_0$  is the permeability. In the magnetosphere  $V_A$  is of the order of 1000 km/s and so a pulsation with a period of 100s has a wave length of the order of  $10^5$  km or  $15R_E$ . This is comparable to the magnetospheric scale so the uniform plasma approximation is invalid.

In a non-uniform medium or magnetic field the two hydromagnetic modes becomes strongly coupled. If we assume a harmonic variation in time and the azimuthal angle  $\phi$ , ( $e^{i(m\phi + \omega t)}$ ), then in a dipole field,  $B$ , the two modes are described by the coupled differential equations

$$\left\{ \mu_0 \rho \omega^2 + h_{\alpha} \underline{B} \cdot \underline{\nabla} \left( \frac{1}{h_{\alpha}} \underline{B} \cdot \underline{\nabla} \right) \right\} (r \sin \theta E \phi) = \left( \frac{\underline{B} \times \underline{\nabla}}{\underline{B}} \right) \phi (\underline{B} \cdot \underline{b}) \quad (9)$$

$$\left\{ \mu_0 \rho \omega^2 + h_{\beta} \underline{B} \cdot \underline{\nabla} \left( \frac{1}{h_{\beta}} \underline{B} \cdot \underline{\nabla} \right) \right\} \frac{E_r}{(r B \sin \theta)} = i m (\underline{B} \cdot \underline{b}) \quad (10)$$

where  $h_{\alpha}$  and  $h_{\beta}$  are geometric factors. However, when the disturbance is transverse ( $\underline{B} \cdot \underline{b} = 0$ ), Eq. (9) is decoupled and describes the poloidal mode in which field line displacement is in the meridional plane ( $\underline{b}$  is radial and  $\underline{E}$  is azimuthal) and which is very localized in longitude. In the case of axial symmetry ( $m = 0$ ), the right hand side of Eq. (10) is zero and then this equation describes the uncoupled toroidal mode in which the field line displacement is in the azimuthal direction ( $\underline{b}$  is azimuthal and  $\underline{E}$  is radial) and L-shells are decoupled.

These decoupled modes describe oscillations of single field lines and so we can calculate the resonant eigenperiod of a given field line. The eigenperiods of

path modes are quite similar. Figure 14 is a sketch of how the resonant period of the fundamental oscillation can change as a function of invariant latitude or L-shell. There is a large jump in resonant period associated with the sharp change in plasma density, and hence Alfvén speed across the plasmapause; otherwise the periods increase with the length of the field line.

The decoupling of the two hydromagnetic modes is, of course, an oversimplification. When the full coupled equations are solved (which has only been done in simplified geometries) a fuller picture of the field line resonance structure results. Figure 15 sketches the behavior of amplitude of a monochromatic signal in the region of a resonant field line, as a function of latitude.

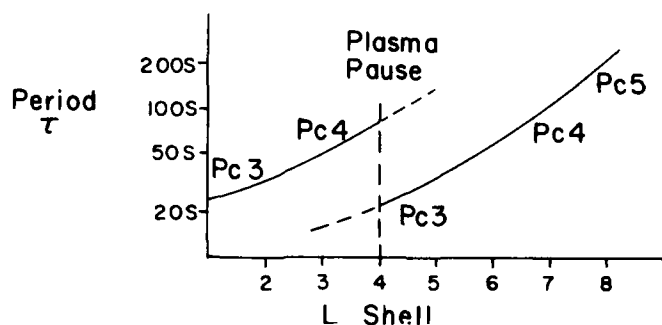


Figure 14. Variation of the Resonant Period of the Fundamental Hydromagnetic Oscillation of a Single Magnetic Field Line as a Function of L-shell (Courtesy of J. Hughes)

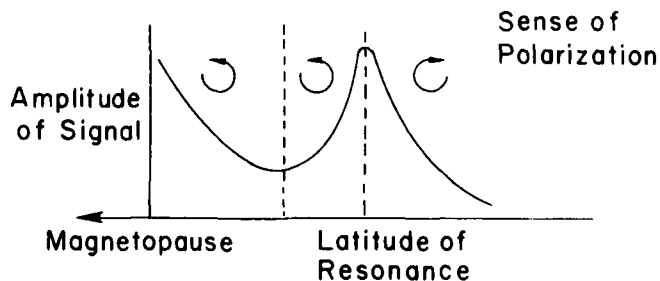


Figure 15. The Amplitude of a Monochromatic Signal (from a Surface Wave in the Magnetosphere), in the Region of a Resonant Field Line as a Function of Latitude. The changes in the sense of polarization across the extreme amplitude values is also shown (Courtesy of J. Hughes)



The figure is drawn supposing that the wave source is a surface wave on the magnetopause. The amplitude drops off away from the surface except in the region of the field line whose eigenperiod matches the period of the source. Here the amplitude peaks sharply and there is a reversal in the sense of wave polarization. This switch in sense of polarization occurs whatever the wave source and follows directly from the fact that energy flux propagates towards the resonance. In space there is a sharp change in the phase of the azimuthal magnetic field component across the resonant region while the radial component shows much less change. (On the ground the sharp change is seen in the H or North-South component due to the effect of the ionosphere.)

When solving the coupled wave equations described above, it is found that a damping term needs to be introduced in order to remove a mathematical singularity at the resonant field line. There are several ways in which a pulsation signal can lose energy and the overall structure of the signal depends on which method is dominant. In particular the latitudinal extent of the resonant region is governed by the damping rate.

An important and probably the most important source of signal damping is the ionosphere. At the ends of the field line the currents forming the hydromagnetic wave must close in the ionosphere and in so doing lose energy via Joule heating. Another possible source of damping is Landau damping, which in this application involves coupling between particle bounce frequencies and the wave frequency. The generation of kinetic Alfvén waves in resonant regions narrowed to a length scale of an ion Larmor radius might also play a role.

### 3. Ionospheric Effects

Of particular importance to ground based observations such as the AFGL chain is the part played by the ionosphere in the overall process. We have already mentioned that the ionosphere acts as an energy sink. However, the ionosphere also shields signals with short horizontal scale lengths from the ground and causes the polarization direction observed on the ground to be  $90^\circ$  different from the polarization direction in the magnetosphere.

Figure 16 shows why this polarization rotation occurs. A signal with a net energy flux into the ionosphere is shown schematically in the magnetosphere. The electric field in this wave causes both Pederson and Hall currents to flow in the ionosphere. The Pederson current effectively shields the incident signal from the ground (as any signal is shielded by a good conductor) but the Hall current produces a new magnetic field which is the one seen on the ground. As the Pederson and Hall currents flow at right angles to each other, the magnetosphere and ground magnetic fields are also at right angles.

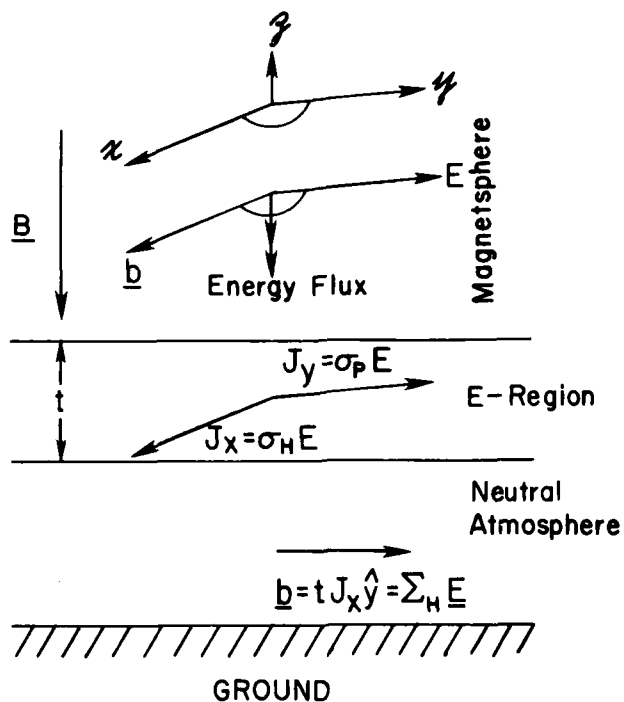


Figure 16. Rotation of the Polarization Direction (by  $90^\circ$ ) in Transmission of a Hydromagnetic Wave Through the Ionosphere (Courtesy of J. Hughes)

The ionosphere also substantially reduces the amplitude on the ground of any signal with a horizontal wavelength much less than  $2\pi$  times the height of the ionosphere E region, about 120 km. The ratio of ground to magnetospheric amplitudes is given by

$$b_g/b_m \simeq \frac{\Sigma_H}{\Sigma_P} \exp(-hk)$$

where  $h$  is the height of the E region,  $k$  is the horizontal wave number of the signal, and  $\Sigma_H$  and  $\Sigma_P$  are the height integrated Hall and Pederson conductivities of the ionosphere. This attenuation means that very localized signals may not be seen on the ground at all, and that all signals will be modified so that sharp spatial gradients will be removed.

The role of the ionosphere as an energy sink is intimately tied up with the structure of the electric and magnetic field perturbations along a resonant field

line. The amount of energy reflected by the ionosphere can be expressed using a reflection coefficient given by

$$R = \left\{ \frac{c^2/4\pi - V_A \Sigma_P}{c^2/4\pi + V_A \Sigma_P} \right\}^2$$

where  $V_A$  is the Alfvén speed above the ionosphere. So of critical importance is the value of the number  $4\pi V_A \Sigma_P / c^2$ . If this number is near unity, strong damping occurs as probably happens at night. During the day we expect this number to be large which would result in low damping and in field lines being approximately fixed in the ionosphere. By this we mean small field line displacement or electric field, and larger field line tilting or perturbation magnetic fields in the ionosphere. If, on the other hand, this number becomes much smaller than 1, which could happen if the conductivity of a dark ionosphere becomes very low, damping is again low, but this time the ionospheric electric field would be large and field lines would act like a free ended string. Presently, a great deal of theoretical effort is going into determining how the perturbation fields along a field line would look for various ionospheric conditions at both ends of the field line. Of special interest are the so called asymmetric modes which occur when one end of the field line is sunlit and the other in darkness, which can frequently happen.

#### 4. Global Extent

A major problem in geomagnetic pulsation studies in the 1970's, both theoretically and experimentally, has been the investigation of the latitudinal extent of pulsation activity. Both the observational and theoretical aspects of this research have resulted in dramatic breakthroughs in the understanding of the localization in latitude of hydromagnetic waves, particularly the majority of the waves observed on the dayside of the earth. While many nightside pulsations, as well as many eveningside pulsations, remain to be investigated and understood, a fundamental problem in the coming few years will likely be the global, longitudinal extent of hydromagnetic waves in the magnetosphere.

A number of papers in the last few years have addressed the issue of the influence of interplanetary parameters on hydromagnetic waves. In general, these studies have been limited to the use of a single groundbased or satellite station in observing the wave activity. However, it is intuitively obvious that if interplanetary processes are important factors in defining the onset, generation, and continuation of hydromagnetic waves, then these waves must exist over a more global extent. Early work by Troitskaya and her colleagues showed the influence

of the interplanetary magnetic field on the onset of hydromagnetic waves as well as, for a single event, the global extent of hydromagnetic waves observed in the Soviet Union and in North America (Texas).

More recently, with results important for the Air Force Geophysical Laboratory chain, are the observations of the simultaneous enhancements of hydromagnetic power observed in the Pc3 band at SANAE Station and at Siple Station in Antarctica (Figure 17). These stations are spaced by approximately 3 hours in local geomagnetic time. Simultaneous enhancements and depressions in hydromagnetic power in this frequency were observed. However, little correlation of individual waves were observed over such a wide longitudinal extent (slightly less than that of the continental United States, the span of the AFGL stations).

In addition, studies were made of the changes, around local noon, in the orientation of the wave polarization ellipses at the two stations (Barker et al<sup>10</sup>). These results show that while the orientation of the polarization ellipses changed around local noon at Siple Station, no such change was observed at SANAE (Figure 18). The results at SANAE could not be attributed to induction effects in the ocean in that no systematical orientation direction of the ellipses were observed. Rather, the authors suggested that the plasma parameters in the magnetosphere changed during the period of time in which the earth's plasma corotated over the observing stations.

The only report on the global extent of hydromagnetic wave control by the interplanetary field was reported by Webb and his colleagues (Webb, et al<sup>11</sup>). These authors showed, for 3 selected days in which the interplanetary field was in the ecliptic plane, that changes of the interplanetary field from a radially-outward to a radially-inward direction apparently affected the overall enhancement of hydromagnetic power in the earth's magnetosphere (Figures 19, 20, and 21).

These problems of the global extent of hydromagnetic energy in the earth's magnetosphere are the key for understanding a large amount of the hydromagnetic character of the earth's magnetosphere and are problems that can be addressed ideally with the wide longitudinal spacing of the AFGL magnetometer network. It is hoped that such studies will be extended and greatly elaborated upon in the coming years.

Another topic of great current interest is the influence of hydromagnetic waves on particle precipitation into the earth's magnetosphere. In particular, using sensitive riometers and balloon-borne x-ray detectors in the conjugate region, low

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10. Barker, M.D., Lanzerotti, L.J., Robbins, M.F., and Webb, D.C. (1977) Azimuthal characteristics of hydromagnetic waves near L = 4, J. Geophys. Res. 82:2879.

11. Webb, D., Lanzerotti, L.J., and Orr, D. (1977) Hydromagnetic wave observations at large longitudinal separations, J. Geophys. Res. 82:3329.

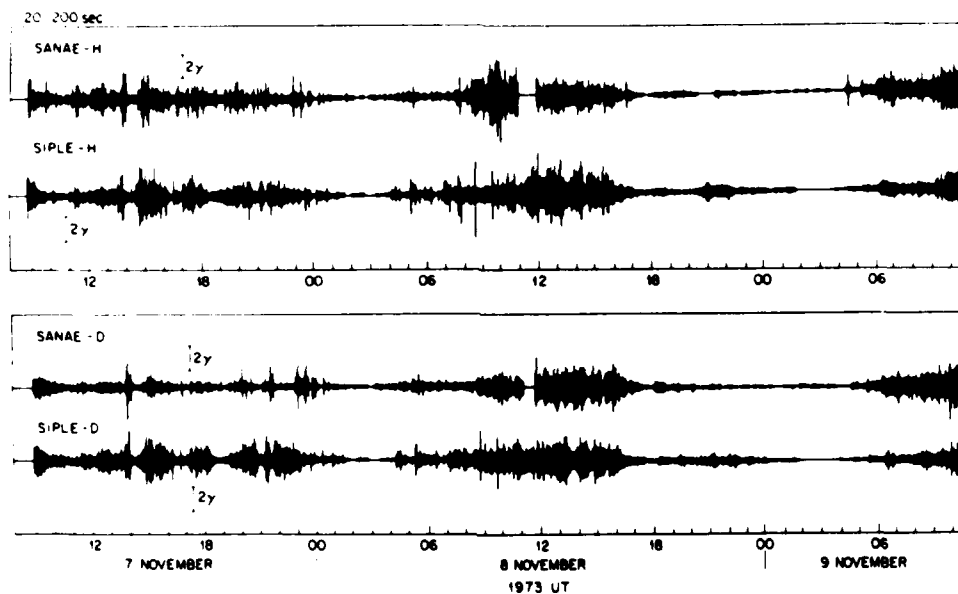


Figure 17. Field Variations (20-200 sec) for November 7-9, 1973, at SI and SA. Data are missing from SA just prior to 1200 UT (Baker et al<sup>10</sup>)

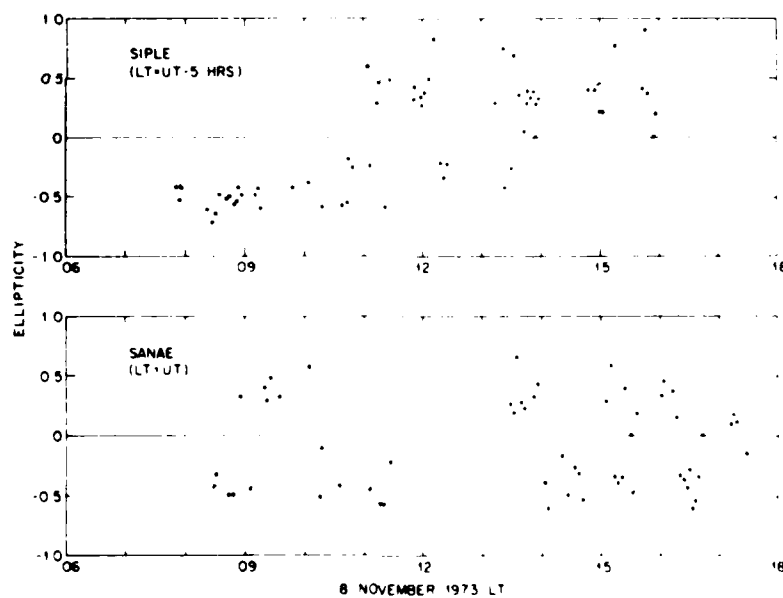


Figure 18. Wave Ellipticities at SI and SA on November 8, 1973, Plotted at the Same Local Times (Barker et al<sup>10</sup>)

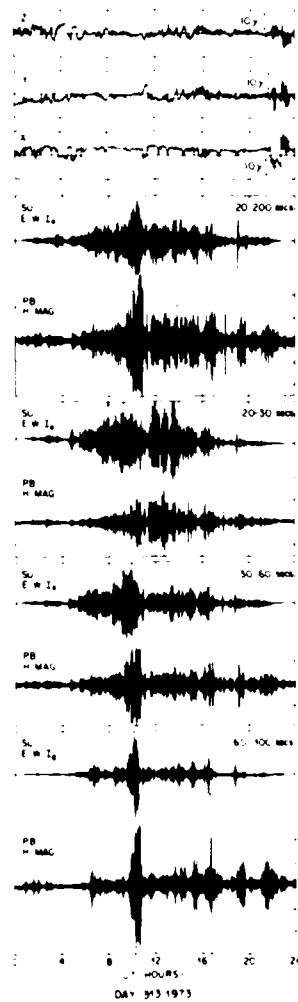


Figure 19. Data from South Uist (SU) and Pittsburgh (PB) for November 9, 1973. The east-west earth current data from SU and the H component magnetometer data recorded at PB have been filtered in the period ranges 20 to 200 sec, 20 to 30 sec, 30 to 60 sec, and 60 to 100 sec, as shown. Also shown are interplanetary field data from Webb and Orr (1976). The three orthogonal components (Z, Y, X) are in the geocentric solar magnetospheric coordinate system (Z is essentially north-south and X is the radial component) (Webb et al<sup>11</sup>)

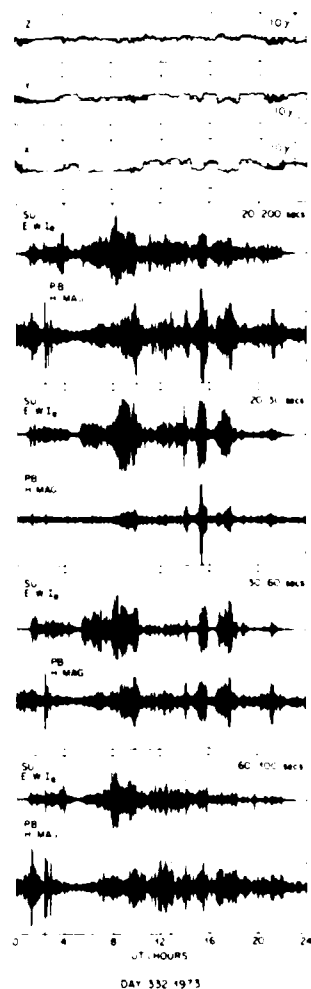


Figure 20. Data from South Uist (SU) and Pittsburgh (PB) for November 28, 1973. The east-west earth-current data from SU and the H component magnetometer data recorded at PB have been filtered in the period ranges 20 to 200 sec, 20 to 30 sec, 20 to 60 sec, and 60 to 100 sec, as shown. Also shown are interplanetary field data from Webb and Orr (1975). The three orthogonal components (Z, Y, X) are in the geocentric solar magnetospheric coordinate system (Z is essentially north-south and X is the radial component) (Webb et al<sup>11</sup>)

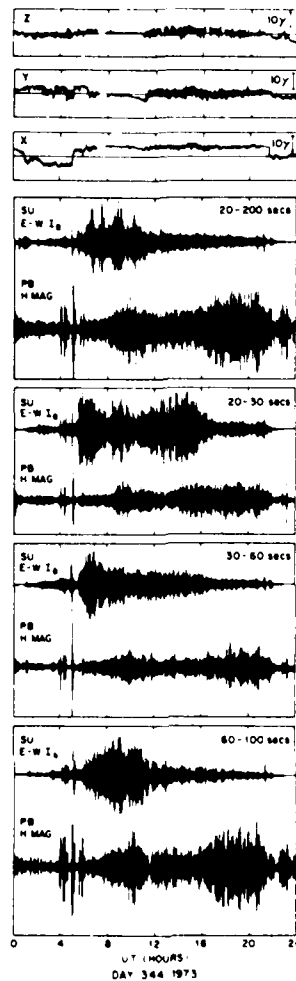


Figure 21. Data from South Uist (SU) and Pittsburgh (PB) for December 10, 1973. The east-west earth current data from SU and the H component magnetometer data recorded at PB have been filtered in the period ranges 20 to 200 sec, 20 to 30 sec, 30 to 60 sec, and 60 to 100 sec, as shown. Also shown are interplanetary field data from Webb and Orr (1976). The three orthogonal components (Z, Y, X) are in the geocentric solar magnetospheric coordinate system (Z is essentially north-south and X is the radial component) (Webb et al<sup>11</sup>)



level particle precipitation into the earth's magnetosphere has been observed in association with hydromagnetic waves. One published study (Maclennan et al<sup>12</sup>) showed that the modulations of precipitation and variations in electric field (measurements made on a balloon) were observed when the hydromagnetic waves were localized near the region of observations (Figures 22 and 23). When the hydromagnetic waves were not localized in latitude near the region of observation, the modulation of the electron precipitation was not observed. Substantially more work in this regard is needed in order to further elucidate the relationship of wave localization to particle precipitation modulation and to the influences on precipitation of wave localization, including the possible generation of the kinetic Alfvén wave in the localization region. This latter process has been investigated in association with the possible generation of sub-auroral red arcs (Lanzerotti et al<sup>13</sup>).

### 5. Pulsation Data Analysis Techniques

During the past decade or so we have seen rapid advances both in the experimental techniques used to measure geomagnetic pulsations and in our theoretical understanding of them. Yet there remains an area between these two, the representation of experimental data, which has lagged behind during these advances, so much so that much analysis is still done using extremely outmoded methods. Data analysis techniques need improving because it is in the representation of experimental data that theory and experiment can be brought together, and so receive the impetus and encouragement they need from each other.

Raw pulsation data usually comprises a series of vector measurements of the geomagnetic field equispaced in time. The analysis of time series data of this type can be undertaken in either the time or frequency domain. In the past much pulsation data was analyzed in the time domain with wave periods measured directly from charts and polarization evaluated by using hodograms. Originally, this was due to the lack of digital data, but by now most magnetometers record digitally. However, even with the advent of digital recorders, many workers still favor time domain analysis because of the difficulty of representing and interpreting the wealth of information derived from spectral analysis.

12. Maclennan, C.J., Lanzerotti, L.J., Hasegawa, A., Bering, E.A., Benbrook, J.R., Sheldon, W.R., Rosenberg, T.J., and Mathews, D.L. (1978) On the relationship of N3 mHz (Pc5) electric, magnetic and particle variations, Geophys. Res. Lett., 5:403.
13. Lanzerotti, L.J., Hasegawa, A., and Maclennan, C.G. (1978) Hydromagnetic waves as a cause of a SAR arc event, Planet. Space Sci., 26:777.

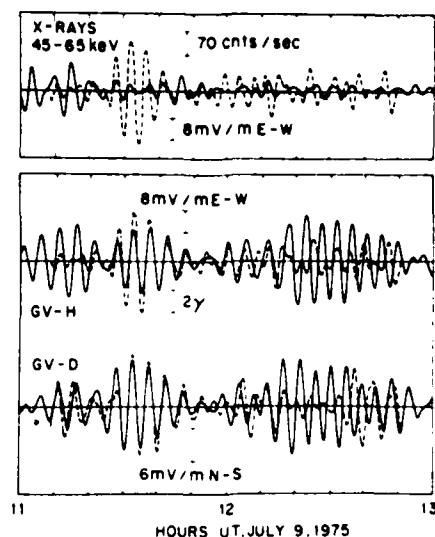


Figure 22. H- and D-component Magnetometer Data from Girardville. Superimposed on the magnetic data are two components of the electric field data measured on a balloon at  $\sim 35$  km altitude approximately midway between GV and I.R. At the top of the figure is the counting rate in the 45-65 keV channel of the X-ray detector. Superimposed is one component of the electric field data. All data have been averaged at 30 sec intervals and filtered in the band 2-7 min (MacLennan et al<sup>12</sup>)

Methods to evaluate polarization information in the frequency domain and to make objective representation of it have been developed (Samson<sup>14, 15</sup>). An example of the use of these methods to analyze a pulsation record follows.

The Fourier transform of a vector time series, such as is obtained from a vector magnetometer, results in the generation of a spectral matrix for each frequency estimate in the frequency domain. This spectral matrix contains all the information about the signal over a discrete and usually small range of frequency space. The problem facing data analysis is how to present the information contained in this matrix in a simple, coherent manner, that makes it readily comparable with theoretical results.

14. Samson, J.C. (1973) Descriptions of polarization states of vector processes: Applications for ULF magnetic fields, *Geophys. J. R. Astr. Soc.* 34:403.

15. Samson, J.C. (1977) Matrix and Stokes vector representations of detectors for polarized waveforms; theory, with some applications to teleseismic waves, *Geophys. J. R.* 54:583.

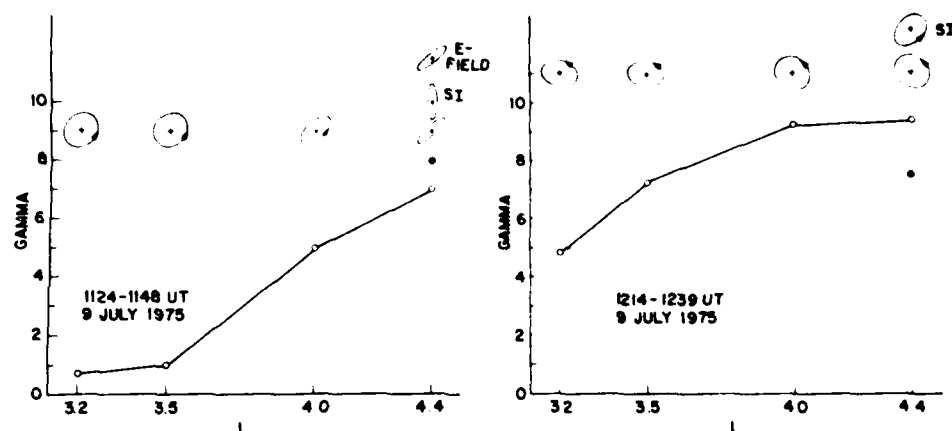


Figure 23. Amplitude of the Magnetic Variations at the Peak of the Two Wave Events as a Function of Latitude (L-value). Also shown are schematic representations of the wave ellipse orientations and polarizations in the plane approximately transverse to the local magnetic field. Polarizations are not indicated for the nearly linear hodograms observed at GV and SI in the 1124-1148 UT event. The Siple amplitudes (solid dots) are plotted at L = 4.4 because of the similarities of the ellipticities of the Girardville and Siple events (MacLennan et al.<sup>12</sup>)

The spectral matrix can be represented mathematically as a series of (complex) eigenvectors and eigenvalues. If we start with three components then we require three eigenvectors. By analogy with quantum mechanics, each of these eigenvectors represents a "pure state" that is a single wave signal with no noise. A matrix corresponding to a single wave will thus have one non-zero eigenvalue. In the past workers have found the eigenvector corresponding to the non-zero eigenvalue by first diagonalizing the real part of the spectral matrix, a lengthy and costly procedure when it is done for each frequency in the spectrum.

This diagonalization can be thought of as a rotation of the coordinate system into a system of coordinates aligned with the principal wave directions, for example, one direction would be normal to the plane of polarization. We now recognize that this diagonalization is no longer necessary provided the matrix represents a "pure state," which is usual in pulsation work. Instead the degree of polarization, a measure of how pure a state the spectral matrix represents, can be evaluated directly from invariants of the matrix, that is, from quantities calculated from the components of the matrix which do not change when the coordinate system is changed. If the degree of polarization is high, that is, the matrix represents an almost pure state, then this state can be derived directly from the matrix without any need for diagonalization, a significant computational saving.

In the past we have usually represented the power spectrum of vector data by the power in three spatial coordinate directions. We can picture formally obtaining this information from the spectral matrix by operating on the matrix with an operator formed from the unit vector in the direction of interest. However, by a simple extension of this idea, we can obtain the power in the signal in any given "state" we wish to choose which can be represented by a unit vector in our complex space of states. For example, to find how much power there is in the x direction we would use the vector  $(1, 0, 0)$ ; whereas to find the power in a wave circularly polarized in the x-y plane we would use  $1/\sqrt{2} (1, i, 0)$ . This leads to two new possibilities. First we can represent any wave data, whether of a "pure state" or not, in a nine-dimensional generalized space (the nine dimensions arise from needing nine orthogonal vectors to form a complete complex vector space) from which arises the concept of a generalized power spectrum. Secondly, and this is probably the most powerful new tool presented here, we can, by a simple operation, inquire how much power there is in any given wave "state" we might choose. We can use this to test particular theoretical predictions of wave polarization directly from the experimental data.

To illustrate this last point the analysis of one particular pulsation event will be described. The data in question was obtained from Fort Providence in Northern Canada and is shown in Figure 24. It is the Pc 5 pulsations extending from 1300-1900 UT which are of interest here. Figure 25 shows dynamic spectra of the power in the three components, that is in the directions of the unit vectors of the measurement coordinate system. The power remains at a fixed frequency of about 4 MHz and there is nothing to indicate that we might be near the latitude of a field line resonance described earlier.

As explained in Section I.B.2, the sense of polarization of a pulsation is expected to change across a resonance region. As a first attempt to analyze the waves, the dynamic power spectrum was computed in the directions of right- and left-hand circularly polarized waves in the H-D plane. The results are shown in Figure 26. There is little or no sign of a polarization reversal.

Becoming more sophisticated, we tried to find the actual state vector that has been theoretically predicted in the vicinity of a field line resonance. Such a prediction has been made for ground based data by Hughes and Southwood.<sup>16</sup> Constructing state-vectors from their theoretical results we computed the power in the states expected just North and just South of a resonance region. The results are shown in Figure 27. There is a dramatic improvement over those shown in Figure 26. First, much more power appears in these states. Secondly, there is

16. Hughes, W.J. and Southwood, D.J. (1976) An illustration of modifications of geomagnetic pulsation structure by the ionosphere, J. Geophys. Res. 81:3241.

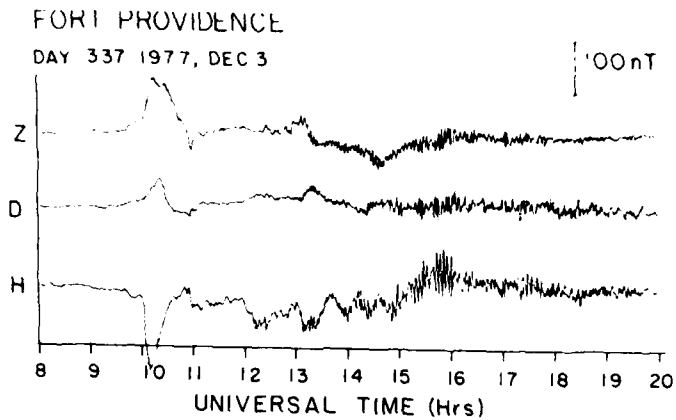


Figure 24. Magnetic Variations Recorded at Fort Providence in Northern Canada, December 3, 1977. Pc5 pulsations extend from 1300-1900 UT (Courtesy of Samson)

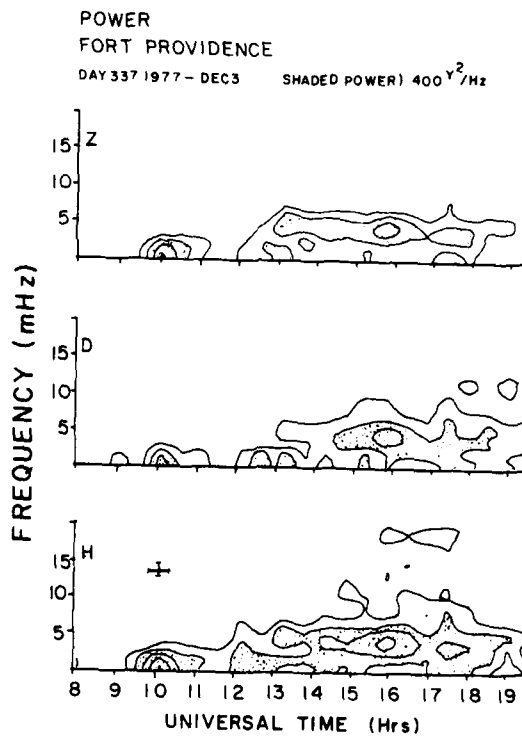


Figure 25. Power Spectra of the Magnetic Variations shown in Figure 24 in the Measurement Coordinate System (Courtesy of Samson)

H-D PLANE  
FORT PROVIDENCE  $D_p = (P \cdot D_2)^2$   
DAY 337 1977 - DEC 3 SHADED AREA  $D_p > 0.5$

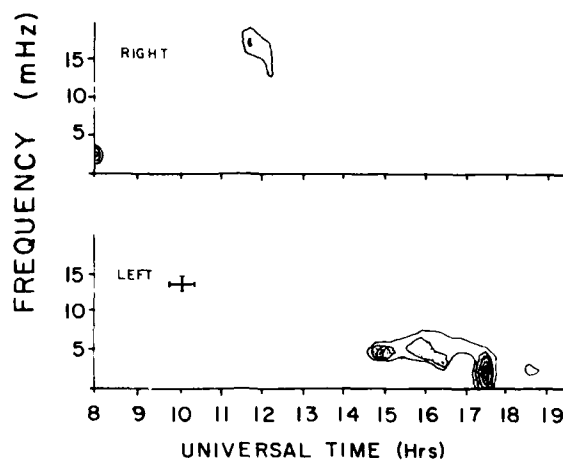


Figure 26. Power Spectra of the Magnetic Variations shown in Figure 24 in the Directions of Right and Left Hand Circularly Polarized Waves in the H-D Plane (Courtesy of Samson)

NORTH-SOUTH  
FORT PROVIDENCE  $D_p = (P \cdot D_2)^2$   
DAY 337 1977 - DEC 3 SHADED AREA  $D_p > 0.5$

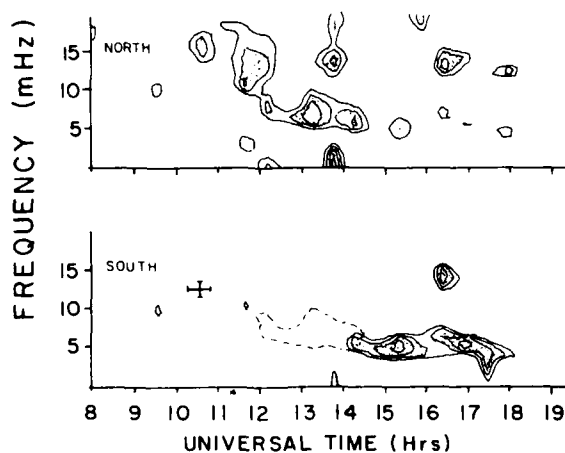


Figure 27. Power Spectra of the Magnetic Variations shown in Figure 24 just North and South of a Resonance Region (Courtesy of Samson)

a sharp change at 1400 UT. Before this time most of the power at 4 MHz is in the North "state vector" whereas after this time it is largely in the South "state vector," thus indicating that the latitude of the resonating field line drifted North passing over Fort Providence at 1400 UT. (The dotted contour in the lower panel shows where most of the power at 4 MHz occurs in the upper panel.)

This example illustrates two major points. First, that this method is very sensitive to the particular state vector chosen, as shown by the dramatic difference between results in Figures 26 and 27. Second, that this method can test actual theoretical predictions easily and directly using real data. It should also be noted that it is simple and cheap as no diagonalization of the spectral matrix is needed. It thus makes a very powerful addition to the data analysts' tools.

## C. APPLICATIONS (Reporter: R. Regan)

### 1. Introduction

The direct practical applications or utility of increasing our understanding in a scientific field is often difficult to identify. In the case of the geomagnetic field, however, and in particular the external field, there are a number of immediate applications that are served directly by the studies reported at this conference. Before discussing such applications, however, it is useful to provide the necessary perspective by outlining briefly some pertinent aspects of the geomagnetic field.

### 2. Constituents of the Geomagnetic Field

The geomagnetic field is conveniently and naturally divided into three parts: internal, crustal (or anomalous), and external. The internal field is the more stable primary field arising in the core region; it is broadscale spatially and contains only extremely low-frequency temporal variations. Routinely monitored by magnetic observatories, repeat stations, and satellites, it is well described quantitatively by mathematical field models, which serve as reference standards for the reduction and analysis of most magnetic observations.

Superimposed on this field is one of higher spatial frequency arising from the fact that certain materials and structures in the crust (the outermost tens of kilometers of the earth) modify the internal field. Long the object of natural-resource investigators, this field is routinely mapped by ground, air, ship, and satellite measurements to aid in the search for minerals and fossil fuels.

The third component, the external field, is undoubtedly the most dynamic, complex, and elusive. One might more accurately say external fields (plural), since this component arises from many sources in the complex interaction between terrestrial and solar magnetic fields and in other physical processes associated with the solar-terrestrial environment. It is useful to separate these sources into the broad categories of ionospheric and nonionospheric.

The important common factor that affects all applications (and even theoretical studies) of the geomagnetic field is the fact that any measurement of the field is a composite of these three components. Because of this factor there is a need for communication between investigators having primary interests in different facets of the field. At the least, each must have a knowledge of the other components for the purpose of removing them to isolate the signal of primary interest. In the areas of practical applications, this complementary signal/noise relationship is the basis underlying the need for a better understanding of the external fields.



### 3. Crustal Anomalies and the Search for New Natural Resources

Nowhere is the need for good external-field models more evident than in the mapping of the anomalous field. As known supplies of natural resources diminish, the search for new resources takes on a new importance. Anomalies in the crustal field often lead to resource deposits. However, magnetic surveys are no longer conducted to map the most obvious anomalies. Rather the effort now is on broad-scale studies focusing on more subtle secondary indicators of such deposits. Such an objective demands more accurate measurements of the crustal signal over sizable regions of the globe. Up to the present, the development of instruments, both for direct measurement of the magnetic field and for supporting measurements (such as positional location), has been the limiting factor in such surveys. Now, however, the limitation is how accurately the anomalous signal can be extracted from the measurement of the total field. As the result of the concerted efforts of a number of workers over the past few years, it is now routinely possible to remove the effect of the internal field from total field measurements by subtraction of an accurate geomagnetic reference field. However, the same is not true for the external field. Indeed, we are just entering an era in which both the need and the inability to correct for external (temporal) variations is becoming very apparent (Langel et al,<sup>17</sup> Sugiura and Hagan<sup>18</sup>).

It is now accepted practice, when making magnetic survey measurements, to set up a temporary fixed magnetometer station for recording the temporal variation of the magnetic field. Then, under the assumption that the measured temporal variation affects both the fixed monitoring station and the survey magnetometer in the same fashion, the variation is removed from the survey data. However, there are several problems with the assumptions made in this technique. One involves the coherency of the input signal; another involves the effect on the input signal of the heterogeneous conductivity of the solid earth. These two factors, not previously treated in a fashion adequate for the needs of magnetic surveys, reduce the effectiveness of this technique and limit its use in routine applications. The most desirable method of accurately removing external-field effects would be the use of accurate mathematical models, similar to those for the internal field, to account for the various external sources. If such models existed, survey data could be

17. Langel, R.A., Fabiano, E.B., and Mead, G.D. (1978) The Utility of Surface Magnetic Field Measurements in the MAGSAT Program, NASA Tech. Mem. 79614.

18. Sugiura, M. and Hagan, M.P. (1979) Geomagnetic Sq Variation at Satellite Altitudes: Is Sq Correction Important in MAGSAT Data Analysis?, NASA Tec. Mem. 80248.

corrected accordingly, and a magnetic anomaly could be defined to be the measured field minus the internal and external fields (Regan and Cain<sup>19</sup>).

#### 4. Terrestrial Conductivity

Complementary to the mapping of the anomalous field for resource studies is the use of the external field signals to map the structure of terrestrial conductivity. Such studies, which are primarily useful in resource studies and in the investigation of the gross internal structure of the solid earth, also are useful in developing effective external-field corrections for magnetic surveys and in determining the response functions of ground-based magnetic observation. In these applications, the aspects relevant to the objectives of this workshop are the need for more accurate definition of external source fields and the need for knowledge of conductivity structures near points where observations of external-field phenomena are made.

Another need for increased knowledge of the external fields arises because they are useful as source fields; no energy is needed to generate these naturally occurring source fields. However, there is no control over the characteristics of these fields, and it is therefore mandatory to have a complete understanding of their pertinent characteristics, particularly their frequency and coherency (Hermance<sup>20</sup>). Frequency determines the depth of penetration, which is related to the skin depth, the depth at which a field of a particular frequency decays to  $1/e$  times its incident amplitude. Thus various external fields have varying degrees of utility in the study of the conductivity at various depths, and it is essential to know both the frequency and the morphology of the particular source signals so that horizontal and vertical discrimination can be made. Additionally, just as a knowledge of the external-field signal is needed in mapping the conductivity structure of the earth, a knowledge of the conductivity environment of external-field monitors is needed for better discrimination of external-field signals.

#### 5. Long Man-Made Conductors

While external-field signals can be profitably employed in the study of the natural conductors of the earth, the same physical effects can be quite troublesome in man-made conductors such as power lines, telegraph lines, and (more recently) long pipelines. Such effects have long been observed, and they are now routinely evaluated each time a new type of long conductor is installed. The conductors

19. Regan, R.D. and Cain, J.C. (1975) The use of geomagnetic field models in magnetic surveys, *Geophysics* 40:621.

20. Hermance, J.F. (1978) Electromagnetic induction in the earth by moving ionospheric current systems, *Geophys. J. Rastr. Soc.* 55:557.

contribute an unwanted effect on the space environment, and they are subject to unique corrosive effects resulting from external-field signals. This is of particular concern in the case of pipelines in the auroral regions, where signals are large and where pipelines are built because of the considerable oil and gas supplies known to exist. Part of the Alaska pipeline, a colossus compared to others in the United States, is located in the auroral regions, where the geomagnetic-disturbance energy may be a hundred times that which troubles engineers at lower latitudes. Auroral activity is accompanied by ionospheric currents, the auroral electrojets, which induce currents in the conducting earth. Such currents are channeled into paths of highest conductivity, either those of geological origin or those, like the pipeline, which are man made. The pipeline has an end-to-end resistance of about 6 ohms. It is essentially a surface-grounded conductor, 800 miles long, running from about  $69.3^{\circ}$  geomagnetic latitude (at Prudhoe Bay on the Arctic Ocean) generally southward to about  $61.6^{\circ}$  geomagnetic latitude (at Valdez on the Pacific Ocean), crossing the region of auroral-zone maximum. Campbell<sup>21</sup> made a series of measurements, mostly in the Fairbanks area, with two magnetometers at 10 and 50 meters from the pipeline. Using the measured variations of the field, the Biot-Savart law, and expected values of magnetic activity indices, he concluded that the induced current would exceed 700 amperes at least once every three years in that area, and even higher values are likely a little further north. Fortunately, the average current in the pipe is only about 1/2 ampere.

Akasofu and Merritt<sup>22</sup> monitored the induced current in a local power-transmission line in the vicinity of Fairbanks, using a grounded-neutral line (138 kv, 100 amps), 166 km in length, running between Fairbanks and the generator site at Healy. By comparing the induced current in the transmission line with records of earth currents and H-component magnetic-field values at College, it was found that the fluctuating currents in the transmission line were clearly the result of auroral induction. On the basis of these measurements and model studies, up to 8 amperes of d.c. current were determined to be flowing in the line.

#### 6. Relationship to the AFGL Magnetometer Chain

In all these practical problems arising from such diverse applications as mapping the anomalous magnetic field, making geomagnetic-depth soundings, and

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- 21. Campbell, W. H. (1977) Average and surge values of electric currents induced in the Alaska pipeline (abstr.), EOS 58:1128.
  - 22. Akasofu, S. -I. and Merritt, R. P. (1979) Electric currents in power transmission line induced by auroral activity, J. Geophys. Res. (submitted for publication).

monitoring the effects of induction on man-made conductors, the common need is for better definition of the external source field. The magnetometer network for the International Magnetospheric Study (IMS) (Lanzerotti et al<sup>23</sup>) was designed toward this end. Included in this design was the AFGL Magnetometer Network. In addition to the stations participating in this study, magnetic observatories are operated by the United States Geological Survey (USGS) throughout North America to monitor not only the external but the internal field as well. The USGS supplements such observations by its well established repeat-survey program, designed primarily to monitor the slow secular variation of the internal field. As reported by Wood at this workshop, the USGS has consistently maintained and improved the magnetic observatories and is currently considering the establishment of new observatories in California and Florida.

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23. Lanzerotti, L.J., Regan, R.D., Sugiura, M., and Williams, D.J. (1976) Magnetometer networks during the international magnetospheric study, EOS 57:442.

## **II. Contributed Papers: Brief Reports**

The contributed papers, between 5 to 10 minutes in length, reflected the same interests and organization of the tutorial lectures.

The first group of papers were on magnetic pulsations with considerable focus on the use of the AFGI magnetometer chain. Papers were given by H. Fukunishi, E. Greenstadt, E. Maple, P. Fougere, and W. Bellew.

The second group dealt with three areas concerning magnetospheric dynamics: current models, magnetic signatures, and magnetic indices. Contributions were from R. Wolf, J. Siscoe, R. Carovillano, M. Sguira, J. Barfield, R. Sheehan, P. Tanskanen, J. Walker, J. Feynman, H. Garrett, and W. Stuart.

The recorders were W. Bellew and R. Sheehan.

## A. GEOMAGNETIC PULSATIONS

(Reporter: W. Bellew)

Contributed papers on Friday afternoon dealt with current measurements of geomagnetic pulsations with focus on the use, both present and future, of the Air Force magnetometer chain.

P. Fougere and W. Bellew discussed two studies of sudden commencements using the AFGL magnetometer network. The study by P. Fougere was of an SSC produced by a very large solar flare of class 3B. The accompanying shock wave from the sun travelled with an average velocity of 714 km/sec. The magnetometer chain shows that the resulting disturbance on the earth travels from west to east, attenuating as it moves eastward. If the disturbance is sweeping across the earth from the sun it might be expected that the stations would respond in the order of their distance from the sub solar point, that is, for the case studied, easterly as observed.

W. Bellew, in a study of 17 SSC's occurring in 1978 demonstrates the superiority of the search coil magnetometer to the flux gate magnetometer both for identification of sudden commencements and for revealing micropulsation activity preceding the events. Other fine scale features that can be followed in time across the chain are also apparent only in the search coil data.

E. W. Greenstadt reviewed current work in the origin of medium-period geomagnetic pulsations. Determination of what the correct relationships are between pulsations and the geomagnetic environment is currently under study by several groups. There is little doubt that some connection exists between the solar wind and pulsation activity at earth's surface. The Pc3 amplitude rises with increased solar wind velocity and with decreasing cone angle. (Cone angle is the angle between the IMF and the solar ecliptic x-axis.) There are two principal models for external stimulation of magnetospheric waves and pulsations. In one, the solar wind velocity to drive magnetopause surface waves (Kelvin-Helmholtz), and in the other, waves forming part of the quasi-parallel bow shock structure are transmitted into the magnetosphere.

Greenstadt suggested five areas of research for further investigation. They are 1) improvement of Kelvin-Helmholtz model in the noon-midnight meridian, 2) development of a quantitative signal model, 3) development of a global pulsation activity index or "input level", 4) correlation of the input level with solar wind parameters, and 5) tracing specific signals through plasma regimes from the solar wind or magnetopause to the ground. The Air Force magnetometer system can make significant contributions to the last three areas. One necessity for improved data on pulsation origin, both for statistical and individual-case

approaches, is a set of ground stations insulated from the strongest sources of geomagnetic variability but responsive to wave signals. Some latitudes are much better than others. Pulsation period varies with geomagnetic latitude and is subject to dynamic variation caused by changing plasma density in the plasmatrough. This dynamic variability affects pulsation amplitudes through changing resonance periods and is probably responsible for much of the scatter in correlation diagrams. There are diurnal contributions to the plasmatrough variation where characteristic density enhancements are visible at certain local times.

The Air Force chain is advantageously situated for monitoring Pc4 pulsations comparatively free of plasmatrough variability and should be equipped with the computing and communication hardware, software, and staff necessary to take advantage, through internal or external usage, of its unique potential.

H. Fukunishi reported the results of a statistical study of the spectral elements of magnetic pulsations measured by induction magnetometers at Syowa and Mizuho stations in Antarctica and at Husafell which is in the conjugate area of the former two. The maximum entropy method was used to calculate power spectra of the H and D components at the three stations, phase differences and coherencies between H and D components at three stations, polarizations, major axis orientations and ellipticities in the H-D plane at three stations, and phase differences and coherencies of H and D components between two stations. He found that the major axis direction switches across local magnetic noon, while the power intensity decreases greatly during the afternoon hours. This relationship suggests that magnetic pulsations observed near  $L \sim 6$  in the daytime are odd mode standing oscillations of local resonant field lines excited by compressional waves, and that the location of local resonant field lines changes as a function of local time. The resonance region may be located near  $L \sim 6$  in the morning hours, while it may shift toward low latitudes during the afternoon hours.

E. Maple discussed the polarization of geomagnetic pulsations and magnetospheric resonances. The discussion was based on data recorded at Strawberry Hill, Mass., using induction coil sensors. These data show many occurrences of linear superposition of pulsation wavetrains of different periods. The polarization of the individual wavetrains can be observed by proper band-pass filtering (filters of about one octave width can minimize superposition).

Strong polarization trends of many sections of the data show that many of the pulsations originate from hydromagnetic wave activity. The occurrence of elliptically polarized wavetrains persisting for two cycles or more, which constitute half the data sample, are also indicators of hydromagnetic wave activity.

For April 18, 1965, the number of polarization runs (maintenance of the same sense of polarization for one complete  $360^\circ$  rotation) are examined as a function of

period. The periods for peaks in occurrence form a geometric progression with a ratio of 1.7 between successive periods. The data are interpreted as a geometric series of magnetospheric resonances with a fundamental period of about 5 minutes.

The widths of the peaks of the distributions and the short average length of the polarized wavetrains show that the resonances have low Q's of about 4 or 5. The implied energy losses presumably occur in the ionosphere, although wave-particle interactions at higher altitudes may also occur. A large magnetic storm (maximum Kp 8-) occurred on the night of 17-18 April 1965, and the station was inside the southern boundary of the expanded auroral oval from 0000 to 0600 EST. The large pulsation amplitudes observed during the storm indicate that the strong source of energy exciting the resonances during the 0000 to 0600 EST interval was different from the weaker excitation source for the following 0600 to 1230 EST interval. The resonances were essentially the same during both intervals.

It would appear to be very difficult to develop a theoretical basis for the geometric series of resonant frequencies that has emerged from the present analysis. It must be noted, however, that previously published observational data provide as much support for a geometric series as for a harmonic series. A reconciliation between theory and observations awaits further investigation.



## B. MAGNETOSPHERIC PHYSICS

(Reporter: R. Sheehan)

The Saturday morning session of contributed papers in the AFGL workshop included three areas of interest to users of AFGL magnetometer data: models involving magnetospheric and ionospheric currents, ground based or satellite magnetic signatures, and magnetic indices. In this summary the grouping of talks is done according to the topics mentioned above. Although some talks overlapped two areas, the emphasis of a presentation usually made the choice reasonably easy.

A model described by R. Wolf uses satellite data to obtain the polar cap potential drop and global conductivity pattern as inputs, from which self-consistent plasma motions and currents in the magnetosphere are computed. Midlatitude magnetic signatures derived from the Biot-Savart law prove to be very sensitive to details of the magnetospheric-ionospheric current systems. Comparisons with an example of AFGL magnetometer data show some agreement in gross features but not with much detail. In a similar vein, the complicated influence of a magnetospheric current system was discussed by G. Siscoe, who represented the combined Region 1 and 2 field-aligned current systems in an unusual way. By considering the currents as two offset rings of in and out currents impinging on the ionosphere, the magnetic effect at the earth's surface comes from a dipole-like source which depresses the main field at dusk. The partial ring current is thought to cause this depression, but, as this treatment suggests, a part of it might be due to contributions from other current systems.

R. Carovillano presented a model which calculates ionospheric electric fields from field aligned current inputs and a global ionospheric tensor conductivity model. An interesting result of the work is a clockwise rotation of the polar cap electric field direction as the strength of the Region 2 (equatorward) field aligned current system increased in strength relative to the Region 1 system. M. Sugiura's modeling procedure, on the other hand, uses ionospheric potential and conductivity patterns as input and calculates the field aligned currents necessary to keep the current density non-divergent. With uniform conductivity, field aligned currents corresponding to Regions 1 and 2 were found at the inflections of the potential. Enhanced auroral zone conductivity shifts the field aligned currents relative to the potential and causes the region 1 system to be the chief one.

Comparisons between midlatitude magnetic signatures and observations at synchronous orbit were discussed by J. Barfield. He noted that the two sets of signatures were often similar when substorms were known to be occurring. However, the D component at synchronous orbit can be affected by the position of the satellite relative to the magnetic equator. His conclusion that ground based

magnetometers at midlatitudes were in a good position to observe substorms was supported by a qualitative indexing scheme introduced by R. Sheehan. Based on magnetometer data from Fredericksburg and Boulder, the results showed that if stations from a midlatitude longitudinal sector were used to describe auroral zone magnetic activity, as would be the case with the AFGL chain, the local time variation of midlatitude signatures became important. The local time sector near dawn appeared to be an area at midlatitudes which is least sensitive to auroral zone disturbances causing AE enhancements.

P. Tanskanen showed a DMSP satellite image with spectacular torch-like tongues of aurora extending to high latitudes. During the hour prior to this image, the AFGL chain stations recorded long period oscillations of periods about a 1.2 hour or longer. He speculated that the oscillations could be related to currents on the same spatial scale of the large auroral features. Rough hodograms from the data exhibit counterclockwise elliptical polarization of increasing amplitude.

One consequence of ionospheric currents in the polar cap and auroral zone is Joule heating. J. Walker commented on these currents and the occurrence of sudden stratospheric warmings which affect the polar vortex, which in turn influences global climate. There is a correlation between temperature changes in the stratosphere and AE, but the fact that there are many substorms over a winter season, but only a few stratospheric warmings, indicates that other factors are involved, such as solar proton enhancements.

Results of comparisons between mid and high-latitude magnetic indices were presented by J. Feynman. When the ratio of aa, a midlatitude index, to AL is plotted against aa there is considerable scatter which cannot necessarily be attributed to inaccuracies in deriving the indices. This implies that different causes contribute to the indices. Correlation of both AE and ap with several solar wind parameters also indicate that different processes govern the behavior of AE and ap. In a related example it was observed that world wide H component fluctuations on the order of 10% at midlatitudes often do not appear related to substorms and high-latitude magnetic bays. Such fluctuations occur during noisy periods in the IMF. H. Garrett used 11 years of solar wind data to study correlations at increasing time lags between magnetic indices and various combinations of solar wind parameters. AE showed the best correlation with  $v^2(B_z)$  in the solar wind. On the other hand,  $D_{st}$  showed the highest correlation with itself, a finding probably related to the persistence of velocity in the solar wind. Solar wind parameters involving the IMF or its variance have shorter time scales. Magnetic indices having correlations with these parameters at near-zero lag time lose their correlation rapidly at longer lag times.

A final note by D. Southwood, speaking for W. Stuart, informed workers that magnetic stations located in Scotland and Finland were approximately at the same geomagnetic latitude as the AFGL chain. These stations would extend the chain sufficiently to allow coverage over nearly 12 hours of local time.

### III. The AFGL Chain: Workshops

Workshops were held at the end of the conference for the specific purposes of integrating the measurements from the new AFGL mid-latitude magnetometer chain with current research efforts within the wider geomagnetic community and examining users needs in this regard. Again, the division of interests was a three-fold one: magnetospheric disturbances, geomagnetic pulsations, and applications. Each participant elected the workshop of greatest interest for his or her own work. A questionnaire (Appendix B) was distributed to better focus discussions. For each workshop the chairman and reporter prepared joint reports which are given below. In addition, several participants gave individual responses to the questionnaire. These are included in Appendix C.

The workshop chairmen were J. Feynman, L. Lanzerotti and W. Campbell. The reporters for the respective sessions were: J. Barfield, J. Hughes, and R. Regan. R. Carovillano chaired a summary session of all workshops.

## A. WORKSHOP ON MAGNETIC DISTURBANCES

(Chairman: J. Feynman; Reporter: J. Barfield)

The Workshop on Magnetic Disturbances was held at Air Force Geophysics Laboratory (AFGL), April 7, 1979. This summary report represents the major points of discussion during the two-hour session. The purpose of the workshop was to examine ways in which the AFGL magnetometer chain and other magnetometer chains could be best utilized for environmental monitoring and prediction both in a research and a service capability.

The AFGL chain is unique in that it spans a longitudinal range of 3 hours at  $55^{\circ}$  geomagnetic latitude. British stations already exist at the same latitude which would permit an extension of the chain to cover 8 hours. Because of its unique position the AFGL chain provides information on magnetospheric parameters that are not readily available from other existing chains. The pi2 micro-pulsations observable at these latitudes are good indicators of substorm occurrence. The longitudinal extent of the chain can be used to determine the location of the substorm current system for a considerable range of universal time. The addition of the British stations to extend the longitudinal range would be very desirable. High resolution data would be needed for the pi2's and the longer time scale would be suitable for the current systems. Also, the pi2's offer an opportunity for short lead time substorm prediction whereas substorms can be monitored by the "regular run" data. The east-west orientation of the chain provides an important capability for studying propagation of magnetic disturbances and is useful in investigating the asymmetry of substorm and storm current systems. In addition the prediction of midlatitude perturbation maps could be undertaken. This type of analysis has been developed by McPherron in his studies of global disturbances.

A number of new activity indices were discussed by the participants in the workshop. It was agreed that while the traditionally available indices (Dst, Kp, AE, etc.) are generally adequate for characterization of the overall magnetospheric condition, additional indices are needed which would give information on processes occurring within the magnetosphere. Indices which could possibly be formulated in real-time using the AFGL magnetometer data are: 1) A spectral index giving the magnetic wave power in significant passbands. The AFGL data could be fed through a group of appropriate filter bands and the output time averaged to produce an index of wave power in each passband. The wave index could be combined with realtime magnetic data from the GOES synchronous satellite, to produce a substorm alert package. 2) A real-time Q index as an indicator of the size of the auroral oval. It might be possible to produce a real-time Q index using combined data from the AFGL chain, the IMS auroral magnetometer chains, and the DMSP satellites.

In addition, it was felt that the midlatitude substorm activity index being formulated by Sheehan using the AFGL data would be a valuable complement to the AE index. This index would not only supplement AE, but could be generated in near real-time. At present, the usefulness of the AE index is significantly degraded by the lag of several years between the occurrence of the geomagnetic activity and the production of the index.

It was noted that magnetometer data from synchronous satellites could be used to "calibrate" the observations made using the AFGL magnetic chain data, and vice-versa. Recent work by Barfield and McPherron using observations of substorm current systems from simultaneous satellite and ground observations shows that use of data only on the ground or in space leads, in general, to a distinctly different interpretation of the substorm sequence than that given by the combined observations.

It was felt that the data dispersal methods now used by the AFGL network are adequate for examining special events. However, the usefulness of the network would be much enhanced by the introduction of a modern computer based data access system. The system should include supporting application programs and would accommodate broad-based studies. The development of such a system is by no means a small task, but the resultant increase in the accessibility of the data would permit studies to be undertaken that would otherwise be impossible. A strong interaction between the AFGL magnetometer chain personnel and the rest of the scientific community would greatly enhance data utilization. This interaction could be accomplished by a number of mechanisms: retaining outside scientists as consultants to AFGL, with access to AFGL computing services; visiting scientist programs; summer study programs; and organization of workshops to attack specific and well defined unsolved scientific problems.

Concerning plans for ground magnetometer networks in the post-IMS period, the group noted strong concern over the possibility that the IMS magnetometer network will be terminated at the end of 1979. The usefulness of magnetometer network data is best demonstrated by studies combining network data with satellite and other correlative data. This process takes a significant amount of time, so that the network is only now beginning to show its power. The problem of the delay in combined studies has also been compounded by the fact that there is a significant time delay between collection of the data and its general availability.

It was also noted that there was a problem with lack of acknowledgment of use of the data by scientists. Whereas the data is beginning now to be used, the Washington agencies are not aware of it unless specific acknowledgment is made. In addition, continuation of the network is important for future studies; it is not feasible to take data for only special events, since it is not known beforehand when the interested events are going to occur.

The discussion then centered on two hurdles to continuation of the IMS network: NSF is somewhat skeptical about continued funding, and the satellite data system that relays the network data is a temporary arrangement, and it might be necessary to timeshare a commercial satellite - TV channel in order to collect the data.

It was agreed that the two problems would have to be addressed and solved in order to continue the network operations. However, the group felt that those problems were outweighed by the value of the network data. It was noted that the network system is only now achieving 95 percent efficiency, and that after such an investment of money and effort, it would be a great waste to shut down the system. The following projects will need the support of both the IMS and AFGL magnetometer networks in the future: SCATHA, MAGSAT, DE, OPEN, POLAIRE, ISEE-C, GEOS-2, DMSP, and environmental monitoring.

In conclusion, it was the consensus of the workshop group that the AFGL magnetometer chain represents a unique and valuable facility for environmental studies. In order to most fully realize the potential of the AFGL data, AFGL must interact strongly with the scientific community to ensure exchange of information and ideas. AFGL should establish a data base management system, so as to assure choice of a proper format for the data and easy access to it. Having done this, AFGL will be in a position to provide a critical element in the U.S. and global environmental monitoring system.

Attendees: J. Feynman, Chairman; J. Barfield, Reporter; S. Gussenhoven, W. Hall, J. Joselyn, R. McPherron, V. Patterson, R. Sagalyn, M. Shea, R. Sheehan, G. Siscoe, W. Stuart, J. Walker, R. Wolf.

## B. WORKSHOP ON GEOMAGNETIC PULSATIONS

(Chairman: L. Lanzerotti; Reporter: J. Hughes)

The workshop discussion on pulsations was attended by about 20 interested people and discussion centered on four main topics: 1) Organization and presentation of the AFGL network data, 2) Specific research projects for which the AFGL network would be useful, 3) A possible follow-up workshop to be held six months to a year from now and 4) The research the participants planned to do in the next year.

The ideas raised in the discussion of these four main topics are collected under their respective headings. Occasionally included are ideas put forward outside the framework of the formal workshop in discussions during the 2 days of the meeting.

### 1. The Organization and Presentation of the AFGL Network Data Set

The meeting stressed that in order for any data set to be used efficiently for scientific research it must be well ordered, as free as possible from error and presented in such a way that it can be easily scanned to find what is present in it. This applies equally well to a data set intended for in-house scientific use as well as to one intended for use by outside investigators.

It was clear that a great deal needed to be done to the AFGL data in order for it to reach this stage. A conflict exists at AFGL between doing in-house research and providing data for outside potential users. It was pointed out by both Eugene and Knecht that AFGL is not a service organization, nor is it about to become one, and that manpower and resources are quite limited. However, the meeting was able to describe some absolute minimum requirements for data presentation even if it is only to be used for in-house research. These requirements are:

- a. A data log indicating in some detail the times that data is available and from what stations.
- b. Storage of the data on magnetic tapes in a form compatible with large computers. It would probably be best to have two sets, one containing only the flux-gate data and the other containing the search coil data with or without the addition of the flux-gate measurements. An additional set containing 1-minute averages of the flux-gate data would be useful though not for pulsation work.
- c. Daily magnetograms from all the stations. It was understood that these are already available.
- d. Plots that can easily be visually scanned to identify pulsation events. These are needed for two frequency bands; the Pc3-4 band (periods between 20 and 200 sec), and the Pc1 band (periods less than 10 sec). Periods longer than 200 s

are relatively rare at midlatitudes and can sometimes be seen on the daily magnetograms. Stuart pointed out that the "typical" pulsation at these latitudes has a period of 90 sec. and an amplitude of 5nT - Pi2 at night and Pc4 during the day time.

The method favored by most to cover the longer period band was to plot the search coil data, averaged over intervals no longer than 5 sec., on a compressed time scale (12 hour or daily plots). This has the advantage of being easy and inexpensive to produce and quick to scan. An amplitude envelope would be visible and since the natural geomagnetic spectrum weighted by the search coil response produces a maximum response in the Pc3-4 frequency range, a large envelope would indicate the existence of power in this band. The disadvantage of this method is that only the existence of activity can be determined without any clue of the frequency or type of wave. A second method which would overcome this problem would be to plot high pass filtered flux-gate data on a more expanded time scale, for example, 10 min/inch. This would allow much more information to be gleaned directly from the plots, such as wave period, amplitude, wave type, etc., but at the expense of a large number of plots. This could effectively be done however if programs existed to filter and plot specific data intervals at short notice, with the possibility of doing quite extensive intervals.

There was less agreement about either the need or method of producing a higher frequency wave index, which could have been because there was no "Pc1 buff" present. A plot indicating power at frequencies greater than 0.1 Hz would seem to be most popular, maybe produced as one plot per day.

There was even less agreement on the need for further routine analysis or on customer service analysis. Lanzerotti likened the problem to that of a satellite experiment principal investigator who has an obligation to produce a usable data set for the scientific community, but should not neglect his own science to do this. Samson took one extreme view and would have stopped at stage 3 above. However, most people (including Samson) felt that the existence of a standard set of analysis programs is essential for both in-house research and outside users. These should be standard programs with variable input parameters which can be chosen at the time of use. Such a set should contain a spectral analysis program with data sample length and frequency resolution to be decided by the user; a filter program with cut-offs and/or pass bands selected by the user; a plotting package to allow the raw data, spectra and filtered data sets to be presented visually, on scales selected by the user; and other more specific programs which depend on the direction of research at AFGL.

Questions were raised by several potential users of the data as to what they can expect from AFGL. What, for example, should someone do who is interested in scanning 6 months of data for a specific sort of event of interest to him? Would someone be able to do this for him at AFGL and send him data for just these



events; would he be able to come to AFGL and scan the data himself and could he expect to find the data in scanable form, or should he request all 6 months of data on tape? Would data be available at, say, 5 or 10 sec. time resolution? A specific problem was raised by Greenstadt who receives money to analyze this data from another Air Force agency. He asked at what point in the analysis procedure should his agency start paying for the analysis. Most of these user questions had to remain unanswered in spite of the presence of both Fougere and Knecht at the workshop, largely because both manpower and financial resources were still unknown and because the volume of such requests could not be assessed. Users were asked to submit specific plans to Sagalyn, at which time such problems could be dealt with.

## **2. Specific Research Projects for Which the AFGL Network Would be Useful**

Several specific research projects were proposed by members of the workshop, and are presented in outline form in order of decreasing detail with which they were suggested, and the interest that they raised.

a. The study of Pi2's - It was clear at the workshop that Pi2's are going to receive extensive study in the next few years. Pi2's are impulsive wave events, seen clearly at midlatitudes, and which are seen best near 2200 LT and well over the whole night side. They are associated with electrojet intensification (Samson) which is not the same as auroral breakup (Southwood) but they do mark the onset of the expansion phase of a substorm (Fukunishi). The use of Pi2's as a forecasting tool or substorm precursor was raised and discussed and Babcock indicated that the Air Weather Service was "watching with interest".

The AFGL chain makes an ideal network to study midlatitude Pi2's and their relationship to midlatitude bays, and to study the evolution of individual Pi2 events over the whole night side, especially if it would be used in conjunction with data from the stations of Stuart's U.K. network at the same latitude. The relationship between Pi2's at midlatitude and high-latitude phenomena with a view of its development as a diagnostic should also be studied. This could either be an extension of work at Boston College or a separate project.

b. Solar wind ground correlations - Greenstadt indicated the potential of the AFGL network as a series of ground stations to use in correlating ground data with solar wind parameters. Their position below the plasmapause adds greatly to the "stability" of observed pulsations. In particular he envisaged a study using solar wind data from ISEE 1 or 2, and AFGL data. The study should try to develop an "input index" for pulsation signals entering the magnetosphere and other pulsation indices.

c. Magnetosphere ground correlations - The need to study, statistically if possible, the correlation between satellite observations of pulsations in the

magnetosphere and observations on the AFGL network. Both ISEE and the GOES SMS spacecraft were suggested, though neither is ideal. The ISEE orbits should be studied for times when the spacecraft are conjugate to the stations.

d. E-W variation of pulsations - A study of the east-west variation of mid-latitude pulsations, both as a function of frequency and local time was suggested, and met with some enthusiasm.

It was also suggested that several "special" events be selected for detailed study. This was generally agreed to be a good idea as this usually leads to a much better physical understanding. However, a full discussion of this topic is left for the next section.

The lack of local expertise in the lore of pulsations led to some discussion (both inside and outside of the formal workshop) of the best way of undertaking such studies. One suggestion which probably merits further exploration is that studies be undertaken at AFGL with the help of an outside expert collaborator. The collaborator would have a consultative role. He would be called in initially to outline the project in some detail, and the work would be started at AFGL. The collaborator would return periodically at, for example, 3 or 4 month intervals to assess the progress and results and to suggest new ways to approach the problems or overcome existing problems. There would also be close contact via mail or telephone between these visits. In this way AFGL would gain expert input and direction for its projects; the collaborator would gain by participating in a research project which he otherwise could not undertake; and the project as a whole would gain from the AFGL analysis capabilities.

### 3. Special Events Studies and a Second Workshop

A substantial part of the discussion time centered on two related topics. One of these was the selection of specific events for a detailed study and the second was the desirability of a second, follow up workshop with a very specific brief.

One of the results of the IMS has been the organization of workshops to coordinate the study of preselected potentially interesting intervals on a worldwide basis. The intense study of a selected event can lead to a much better physical understanding of the physical processes governing a phenomenon. The workshop thought that the AFGL network data should be used to study specific events and several potential intervals were suggested. Recently, at a IMS workshop in Tokyo, five intervals for the study of pulsations were selected and discussed at a round-table discussion chaired by Professor T. Saito. It was felt that these events should be studied using the AFGL chain, with the aim of having results ready to be reported on in Australia where these intervals will again be discussed at an IMS workshop. The intervals are listed in Appendix A. Two other specific intervals were suggested by Greenstadt and are also described in the appendix.

Most of the participants felt that another workshop, on a more specific topic and with few if any formal talks and much more time for discussion, to be held in 6 months or a year's time would be very beneficial. Some members felt that such a workshop should deal with data from specific intervals, but the objection was raised that already there has been many of those and they have not been demonstratively useful. Other members felt that the workshop would do better to concentrate on a specific subject, for example Pi2's, specific examples of which could be studied between now and this future workshop. In general, specific ideas were:

- a. Keep it small, a dozen to 20 people at most.
- b. Bring in a (fame) theoretician or two.
- c. Limit it, in the main, to ground data people. Satellite people can overwhelm meetings by sheer numbers; though one or two specific satellite people might be a good idea.
- d. Hold it just before the Australia meeting in order to report findings there — especially important if studying the "Tokyo intervals".
- e. Make it a Pi2 workshop; then, the Australia timing is less important and it could be held up to a year from now, time for AFGL to work on this subject. However, both the pulsation and disturbance people like this subject.

The main purpose of such a workshop would be to assess AFGL work up to then and provide new ideas and inputs for it to continue, recognizing the lack of local "experts", and to make a concentrated attack on a specific problem and to discuss the problem informally to find areas of agreement and disagreement.

#### **4. Participants Research Plans**

The chairman asked everyone present to give a brief statement stating what problems they intend to pursue for the next year or so. This was to give everyone an idea of where interests lie and to try for a consensus concerning important problems. The obvious and immediate result of this was that Pi2's clearly emerged as the favorite subject to be extensively studied in the near future. Participants were:

- |                |   |
|----------------|---|
| B. Babcock     | No use made of pulsations presently; Interested in Pi2 studies.   |
| W. Bellet      | Pi2 studies.  |
| R. Carovillano | Midlatitude signatures of substorm activity using AFGL chain.   |
| H. Fukunishi   | (a) Pil and IPDP studies using conjugate data and GEOS data.<br>(b) High latitude characteristics of Pc3, 4 and 5.                          |
| P. Hengere     | Pi2 and SSC studies using AFGL coil and flux gate magnetometer data. Prepare computer software for general studies using magnetometer data. |

E. Greenstadt	Propagation of signals from solar wind to ground (a) by tracing individual events with spacecraft data and ground data. (b) by continuing statistical studies of Pc4 seen by AFGL and S.W. parameters.
J. Hughes	Study of Pi2 using geostationary satellite data (3 spacecraft in E-W chain).
J. Kim	N-S and E-W propagation of Pi3. Network funded through 1979 - proposed for 2 more years.
D. Knecht	Establishing AFGL data base: High and Midlatitude correlations.
L. Lanzerotti	E-W studies using a fine grid of stations: Correlation of Pc3, 4 and 5 with particle precipitation. Quebec stations now operating and will do for foreseeable future - together with riometers.
E. Mapel	No specific plans.
P. Rothwell	User services and work with Fougere.
J. Samson	Pi2's - correlation of Pi2's between high and midlatitudes. Association of Pc5 with shear currents and large E-W electrojets: develop predictor analysis techniques. Network recording will end July 1979 so that more effort can be directed towards analysis.
D. Southwood	Pi2 at ATS 6 - correlation of field and plasma data. Pc3 on the U.K. network - particularly E-W studies. Pulsations and boundary crossings using ISEE 1 and 2 data. (ISEE pulsation work with Hedgecock - Imperial College.)
W. Stuart	Phase and Amplitude variations of Pc pulsations both N-S and E-W. Similar for Pi2 and their association with bays (Samson: What's left for anyone else?) Network good through 1979 - hopeful for the future.
P. Taskanen	Correlation of DMSP photos and particle data. Finish balloon campaign (reported elsewhere) IPDP studies in conjunction with Hedgecock, Raspopov, and Troitskaya.
R. Wolfe	Correlation of AFGL and Bell Labs network data with solar wind parameters - Particularly Pc3 and 4.

In summary, the meeting did not reach any definitive conclusions, but there was much interesting discussion and many suggestions put forward which are included in this report.

**C. WORKSHOP ON APPLICATIONS**  
**(Chairman: W. Campbell; Reporter: R. Regan)**

A workshop session on Applications (other Disciplines) was held at the Air Force Geophysics Laboratory on April 7, 1979, as one of three concurrent sessions forming the final portion of a Workshop on Geomagnetism. The purpose of this session was to examine ways in which the AFGL and other magnetometer networks could be best used for environmental monitoring and prediction and for applications to other disciplines in both research and service capacities.

Considering the needs of the various application areas, the U.S. Geological Survey plans, the existence of an AFGL magnetometer network, the tenuous nature of the post-IMS study plans, and the state of knowledge of the physics and nature of external field phenomena, the following recommendations and conclusions were made.

First of all, of paramount importance is the need for models of the various external field sources that are accurate at the earth's surface over small temporal and spatial dimensions. Such models can be utilized in the representation of the external fields for their removal from magnetic surveys and in studying the source field function for geomagnetic depth sounding investigations and related studies.

Intimately associated with such a requirement is the need for diverse yet integrated spatial monitoring of the external field such as can be realized by the AFGL network. However, to extend its utility and broaden its application it is recommended that each station be completely calibrated both in terms of instrumental sensitivity and stability and mapping of the subsurface electrical environment. This effort should include standardization of proceedings to be fully compatible with those of the USGS stations and a complete program of absolute value base line determinations. The finite distances over which the data, as seen at an individual station, could be considered as accurately representing the field should also be determined. Also since the USGS plans and operations are quite complementary to many of the AFGL plans, there should be some sort of integrated effort or at least "grass roots" communication established and maintained between the two agencies.

While most of the data collected by the network is immediately applicable to AFGL projects, there is also a need for data such as this to be available to other scientific investigators and to various commercial peers. While it would be admirable to be able to provide each and every investigator with such data in the appropriate format, it is not very practical nor AFGL's mission to do so. However, an effective compromise could be reached by designing, in consultation with active researchers in the field, a uniform data format that would readily serve AFGL and

the urgency of the scientific community's needs. A system should have been developed such that the ALGL network could be used as a permanent monitoring system for external survey operations. Additionally, all the data from the network should be forwarded to World Data Center for general distribution.

In addition to studies of the various external source fielding, there is a need for the development of indicators so that investigators can tell which external source events are active or predominant. Undoubtedly to some degree the various geomagnetic indices that have been developed can be utilized for this purpose. However, there is a definite confusion and exactly what they are and what they are not clearly is not stated. There exists a real and immediate need for a compilation of these indices, especially in the non-magnetospheric regions. Such a compilation report should be generated describing the indices, their generation, especially what they are representative of especially in terms of which external source events are active.

In summary, there are many intermediate and actual studies that are active in the private industry, university, and government sectors that require more basic scientific knowledge and awareness of the dynamic external ionospheric changes and the need for such present day and future requirements. It is essential that a coordinated, integrated program of external field monitoring be initiated, that accurate external field models and indices be developed, and that effective communication be established and maintained between the active researchers in this field and the users of such data.

Attorneys: W. Campbell, Chairman R. Begun, Reporter J. Deane,  
J. Herrington, R. Hutchison, C. Lister-Jones, J. Wood.

## IV. Networks

Participants in the Workshop on Geomagnetism presented descriptions of their networks discussing instruments, locations, data systems, and the availability of their data to the scientific community. Operating problems, future operations, and suggestions for special studies and new observing sites were also given consideration. It is intended that this section serve as a quick reference for users of network data but it is recommended that readers desiring more detailed information than presented here-in refer to the various IMS bulletins and newsletters and to the referenced publications.

We realize that there are networks past and present not acknowledged in this section and suggest that their omission may be a result of the travel or related timing and support difficulties of the responsible individuals and not a reflection on network location or value.

The material on the networks was assembled by R. Hutchinson. Information on individual networks was supplied by D. Knecht of the Air Force Geophysics Laboratory Network; J. Walker of the Canadian Magnetic Observatory Network; W. Stuart of the Institute of Geological Sciences Network; J. Joselyn of the U.S. - Canadian IMS Network; V. Patterson of the Air Weather Service Network; P. Tanskanen of the Scandinavian IMS Network; J. Samson of the University of Alberta Network; S.-I. Akasofu of the Alaskan Network; R. Rastogi of the Indian Network; H. Fukunishi of the National Institute of Polar Research Network; and J. Wood of the United States Geological Survey Network.

## A. AIR FORCE GEOPHYSICS LABORATORY NETWORK

The seven-station magnetometer network of the Air Force Geophysics Laboratory is currently in continuous operation. Five data-collection stations (Newport, Washington; Rapid City, South Dakota; Camp Douglas, Wisconsin; Mount Clemens, Michigan, and Sudbury, Massachusetts) form a 3800-km east-west chain at  $55^{\circ}\text{N}$  corrected geomagnetic latitude. Two others (Lompoc, California, and Tampa, Florida) are separated by 3800 km at  $40^{\circ}\text{N}$  corrected geomagnetic latitude. The principal instruments, identical at all stations, include a three-component saturable-core magnetometer to measure the surface field and a three-component induction-coil magnetometer to measure its time derivative. Sensitivities are about 0.1 gamma and 0.001 gamma-Hz, sampling frequencies are 1 and 5 samples per second, respectively. The data-collection stations are not manned; measurements are made and processed automatically by microprocessor-based equipment at each station. Stations are synchronized and controlled remotely from the data-acquisition station at AFGL in Massachusetts. Outbound control and inbound data-return signals are transmitted on dedicated commercial voice-grade phone lines. Signal propagation times to and from all stations are artificially made to be identical, so sampling times are simultaneous to within about 1 millisecond. Forward-error-correction techniques are used to assure accurate data transmissions. Data from all seven stations are processed and archived in near-real time by a dedicated minicomputer; values of the field and its time derivative are available within 20 seconds of the sampling time.

Although this network was built to provide realtime data required by the Air Force, and its completion during the IMS was largely coincidental, it is a useful new research tool. The last station to be completed, Lompoc, California, came on line in November 1977. Figure 28 shows the geographical locations of the network stations and Table 1 gives coordinate and installation information. The three-letter designations shown for these stations are those chosen by Dr. van Sabben for his standardized list.

One of the principal instruments at each site is the three-component fluxgate magnetometer. It is actually three separate single-component magnetometers combined into one instrument, sharing a common power supply, electronics, and instrument housing. The instrument utilizes both coarse and fine feedback coils which produce a nulling field at each sensor to cancel the ambient component field being measured. Current through each coarse feedback coil is incremented in units corresponding to 64 gammas until the field is nulled to within  $\pm 64$  gammas, the range of the fine feedback coil. Current through the fine feedback coil is the processed output of a sense coil, which results from amplification, filtering to



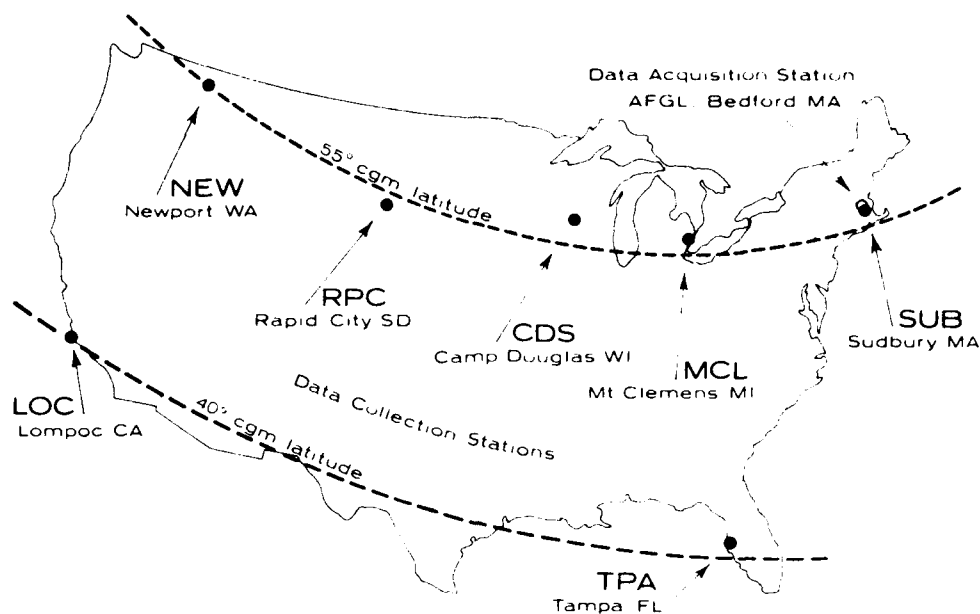


Figure 28. Geographical Locations of the AFGL Network Stations

Table 1. Locations of the Data Collection Stations

Station Symbol Name (Post Office)	Corrected Geomagnetic Coordinates		Geographic Coordinates		Government Installation
	N Lat	E Long	N Lat	W Long	
NEW Newport, WA	55.2	299.6	48.3	117.1	USGS Newport Geophysical Observatory
RPC Rapid City, SD	54.1	317.3	44.2	103.1	Ellsworth Air Force Base
CDS Camp Douglas, WI	56.3	334.2	44.0	90.3	Volk Field (National Guard Base)
MCL Mt. Clemens, MI	55.8	344.8	42.6	82.9	Selfridge Air National Guard Base
SUB Sudbury, MA	55.8	1.9	42.2	71.3	Army Natick Laboratory Annex
LOC Lompoc, CA	40.2	300.6	34.7	120.6	Vandenberg Air Force Base
TPA Tampa, FL	40.7	344.9	27.8	82.5	MacDill Air Force Base

pass only the desired frequency, and demodulation to convert the amplitude to a dc current. This current is proportional to the remaining field (not nulled by the coarse feedback) and is directed through the fine feedback coil to make the total nulling field nearly equal to the ambient component field. The magnetometer outputs are the analog voltage, which produces the fine-feedback current, and the binary count of the coarse-feedback steps. The fine output is low-pass filtered to avoid aliasing which might otherwise result from the low sampling rate.

Each of the fluxgate magnetometers meets the following performance specifications. The fine-feedback section, with a dynamic range of plus and minus 64 gammas, has an output sensitivity of 160 mv/gamma (that is, a full-scale output of 10.24 volts, positive or negative) with a full-scale accuracy of 0.06 gamma. The output filter is a low-pass two-pole Butterworth type with a -3 db corner at 0.3 Hz. The coarse-feedback section with a dynamic range of -65,636 to +65,472 gammas, has a sensitivity of 64 gammas/step (that is, a full-scale output of 1024 steps, positive and negative, with the first positive step being zero field). The output is an 11-bit binary number (including sign) indicating the number of steps incremented. Accuracy is 0.2 percent at full scale positive and negative, with a deviation not exceeding 1 gamma from a straight line between full-scale values. Temperature drift is less than 1 gamma  $^{\circ}$ C in both scale factor and zero-field accuracy. The three component sensors are aligned to within 0.5 degree of orthogonality and are mounted in a single housing equipped with leveling screws and bubble-type indicators.

The second of the principal instruments is the three-component searchcoil magnetometer. It consists of a separate sensor unit for each of the three components and a single electronics unit. Variations in the magnetic field  $dH/dt$  induce a proportional voltage in a long solenoid wound on a highly permeable core. This signal is amplified and filtered for compatibility with the sampling system. The sensor unit comprises about 30,000 turns on a laminated moly-permalloy core. A Faraday shield surrounds the core and winding, and an outer jacket of PVC pipe and endcaps encases the entire sensor unit. Two leads from the sense winding and one from the shield are connected by cables to the electronics unit. In the frequency range of 0 to 5 Hz the sensor alone has a sensitivity of 137 microvolts gamma-Hz. The winding has  $L = 605$  henrys,  $R = 438$  ohms, and  $C = 1350$  picofarads. Four gain settings are selectable on the amplifier (about 5, 10, 50, and 100 times 1000) to provide overall instrument sensitivities of about 0.5, 1, 5, and 10 volts/gamma-Hz. The output filter is a four-pole Butterworth type which provides an essentially flat response from 0.001 to 0.5 Hz; the -3 db point is at 1.4 Hz and the -10 db point is at 2.2 Hz. The -3 db point of the unfiltered output is at 350 Hz.

The stations are generally located in isolated areas of military bases, all are accessible by road and served by power and phone lines. A heated and air-conditioned trailer contains the magnetometer electronics and all other station equipment. Instrument sensors are located on separate heavy concrete piers and are covered with small shed-like enclosures sitting on foundations isolated from the instrument piers. Underground cables connect the sensors to their electronic units in the trailer.

Raw data from the network are recorded in chronological order on archive tapes. The data on these tapes are reformatted and compressed but no information has been discarded. Magnetograms are produced regularly from the filed archive tapes by the network minicomputer. A separate plot is produced for each station along with a composite plot on which the traces of all stations are superposed. The amplitude scale (ordinate) for each station is adjusted automatically to keep the trace on scale, and these differing scales are retained in the composite. The time scale (abscissa) can be selected. Three standard time scales have been chosen for routine use: (1) Daily magnetograms, covering 24 hours from midnight to midnight UT, provide an overall picture of daily activity and the occurrence of storms. (2) Two-hour magnetograms, a 12-fold magnification, permit the identification of sudden commencements and similar features. (3) Twelve-minute magnetograms, a further 10-fold magnification, plot all data samples without averaging and afford the highest resolution.

Inquiries and requests for data may be directed by mail to Dr. David J. Knecht,<sup>24</sup> AFGL(PHIG), Hanscom AFB, MA 01731, or by phone to Knecht (617-861-3828), Tsaooyeanes (617-861-3827), or Hutchinson (617-861-3713). (Autovon numbers are the exchange 478 followed by the last four digits given.) Data will be furnished to the extent permitted by the available manpower and computer time.

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24. Knecht, David J., Hutchinson, Robert O., and Tsaooyeanes, Charles W. (1979) An Introduction to the AFGL Magnetometer Network, Plasmas, Particles and Fields Branch, Space Physics Division, AFGL, Hanscom AFB, MA 01731.

## B. CANADIAN MAGNETIC OBSERVATORY NETWORK

The Canadian Magnetic Observatory Network consists of 11 observatories. The locations of the observatories, their method of recording, and the date at which data commences are given in Table 2.

A digitally recording magnetometer system (AMOS) is the primary digital recorder at all the Canadian observatories with the exception of Mould Bay. The AMOS records values of the orthogonal components of the field and total force  $F$  once a minute on magnetic tape in a format which can be read directly by computer. Depending on the orientation of the sensors the components recorded may be either  $D$  (declination variation in nT),  $H$  (horizontal intensity),  $Z$  (vertical intensity), or  $X$  (north),  $Y$  (east), and  $Z$ . As of January 1975 AMOS at all sites record  $X$ ,  $Y$ ,  $Z$ , and  $F$ .

A set of three component standard-run Ruska variometers recording the  $X$ ,  $Y$ , and  $Z$  or  $H$ ,  $D$ , and  $Z$ , components of the earth's magnetic field is the primary recorder at Mould Bay, and provide an independent analog back-up system at Resolute Bay, Ottawa, Meanook, and Victoria. The time scale of the Ruska magnetograms is 20 mm/hr. The hour marks at all observatories are initiated on the hour by a crystal-controlled clock and last for approximately 15 to 20 seconds.

The three-component fluxgate magnetometer in use with the AMOS provides continuous traces of  $X$ ,  $Y$ , and  $Z$  on a strip chart recorder at all AMOS stations. Full scale chart sensitivity is normally 1000 or 2000 nT, with automatic switching to half sensitivity at times of large magnetic disturbance. The chart is operated at 20 mm/hr. The chart also provides a visual indication of magnetic field conditions.

A second untuned fluxgate magnetometer provides an independent digital back-up system at all AMOS sites.

Microfilm copies of magnetograms and hourly mean tables, and a magnetic tape of AMOS data for each station-year is sent to World Data Center A. Agencies or persons residing outside Canada should request these data directly from:

WDC-A Geomagnetism  
NOAA  
Boulder, CO 80302  
U.S.A.

Digital tapes are removed from the AMOS at the end of each month (plus or minus 1 or 2 days), and sent to Ottawa for processing. A magnetic tape data file, therefore, tends to contain 1 month of AMOS data. The "time lag" referred to below is the period of time after a recording period of 1 month. Similarly, Ruska magnetograms are sent to Ottawa for microfilming at the beginning of each

month and "time lag" refers to the period after the recording period of 1 month.

Table 3 lists the services available and their approximate costs. Prices tend to be flexible; the actual cost may on occasion vary from that which has been quoted.

Additional information may be obtained by calling the Geomagnetic Observatories Section at (613)995-5554.

A number of temporary magnetic variation stations are operating in the Manitoba, northwestern Ontario, and Keewatin District as part of the International Magnetospheric Study (IMS) which runs from 1976-1979. The fluxgate magnetometers at these stations measure the three components of the earth's magnetic field. The signals were recorded on charts in analog form until October 1976 when digital tape recorders were installed at most of the stations. Later in December 1977 a radio was added to some of the magnetometers for real-time telemetry of the data. These real-time data are available the following day while the analog and digital data are available after several months. These magnetic stations, their geographic and geomagnetic coordinates, the type of recorder, the IAGA acronym for the station, and the data intervals are listed in Table 4. Several channels of photometer data are additionally recorded at four locations as indicated. Older magnetic variation stations, which were also in the Manitoba and Keewatin region and for which data are available are also listed in Table 5. There are gaps in the recorded data at all magnetic variation stations because of instrumental failures which have occurred from time to time. No charge is made to cooperating institutions in the case of joint research projects. Additional details are available from the Time Variation, Aurora and Induction Studies Section at (613) 995-5513.

The analog form of the data is a magnetogram which consists of a plot of the horizontal (H), declination (D), and vertical (Z) components of the magnetic field as a function of time which is indicated by hourly marks on the magnetogram. These magnetograms are available as either 35 mm microfilm copies of the original records or as prints (12x enlargements). A second form of the analog data is the reconstituted magnetogram which is plotted from the digital data. However, digital data from the tape recorders are not customarily plotted on a routine basis, and requests for magnetograms would normally carry a surcharge for the plotting. A third form of the analog data is the "stacked" magnetograms from the stations which have real-time telemetry. These magnetograms are of lower resolution than the standard magnetograms but are suitable for a quick look at the disturbance level at a number of stations. Cost of a magnetogram is \$2.00 and that of a microfilm is \$10.00.

The digital data from the on-site tape recorders are available in either the original 10-second sampling rate or in the averaged 1-minute rate. The 10-second data contain the station identifier, date, and time, together with 120 samples of each of the three magnetic elements in each 20-minute record. The 1-minute data also contain the station identifier, date, time, and 60 samples of each component in one 60-minute record. Both data sets are available on standard computer tape in either CDC binary, BCD or EBCDIC, or as a listing.<sup>25</sup> The one-minute digital data are also deposited with WDC-A. Cost of the digital data is \$20.00 for the magnetic tape and \$15.00 for each file for data.

Real-time magnetic data from the six stations (Pelly Bay, Rankin Inlet, Eskimo Point, Back, Gillam, and Island Lake) with telemetry are available the following UT day from the US Space Environment Laboratory. These data are 5-minute averages of the 10-second data and they are stored on-line for 5-10 days. They can be obtained directly from the on-line computer at no charge with a standard ASC II computer terminal operating at 110 or 300 baud. Averaged 1-minute digital data are also obtained from these stations and are available from WDC-A. It is currently planned to close the Churchill line of IMS stations at the end of the MAGSAT mission and to redeploy them for other studies.

Figure 29 shows the location of geomagnetic observatories and geomagnetic recording sites operated by the Earth Physics Branch. These magnetic stations are located in the auroral, cleft and polar cap regions in order to study the large magnetic disturbances found in these regions.

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25. van Beek, G. Jansen (19--) Catalogue of Services for the Division of Geomagnetism, Earth Physics Branch, Energy, Mines and Resources Canada, 1 Observatory Crescent, Ottawa, Ontario, Canada K1A 0Y3.

Table 2. Canadian Magnetic Observatory Network

Observatory Name	IAGA Code	Geographic		Geomagnetic		Elevation, m	Elements Recorded	Date of Commencement of Continuous Recording in Three Elements			
		Lat. N. °	Long. W. °	Lat. N. °	Long. E. °			Analog	Digital		
<b>Northern</b>											
Alert †	ALF	82 30	62 30	85.7	163.7	60	XYZ	Oct 1961			
Resolute Bay	RES	74 42	94 54	82.1	287.7	25	XYZ	Nov 1953			July 1973
Mould Bay	MBC	76 12	116 24	79.1	255.4	40	XYZ	July 1962			
Cambridge Bay	CRB	69 06	105 00	76.7	294.0	17	HDZ				Apr 1972
							XYZ				July 1974
Baker Lake	BLC	64 20	96 02	73.9	314.8	30	HDZ	Mar 1951			
							XYZ	July 1957			Nov 1971
Yellowknife B	YKC	62 28	114 28	69.1	292.7	158	XYZ				Oct 1974
Fort Churchill	FCC	58 48	94 06	66.8	322.5	15	XYZ	July 1957			Sept 1971
Great Whale River	GWC	55 18	77 45	66.8	347.2	25	HDZ	Jan 1965			Oct 1972
							XYZ				July 1974
<b>Southern</b>											
Meenook	MEA	54 37	113 20	61.8	301.0	700	HDZ	Sept 1931			Nov 1970
							XYZ				July 1974
St. John's	SJJ	47 36	52 41	58.7	21.4	100	HDZ	Aug 1968			Dec 1969
							XYZ				July 1974
Ottawa	OTT	45 24	75 33	57.0	351.5	75	HDZ	July 1968			Sept 1970
							XYZ				Jan 1975
Victoria	VIC	48 31	123 25	54.3	292.7	185	HDZ	July 1957			Nov 1970
							XYZ				July 1974
Whiteshell	WHS	49 48	95 15	59.9	325.3	336	XYZ				Jan 1976

Assuming geomagnetic pole 78.3°N, 291.0°E (Finch and Leaton, 1957).

† Variation stations with limited absolute control.

Table 3. Canadian Observatory Data Services and Costs

<u>Types of Data</u>	<u>Description</u>	<u>Time Lag</u>	<u>Cost</u>
Analogue records	-hard copy of magnetogram or plots of digital data; digital data are instantaneous values and not electronically averaged or filtered	3 weeks	\$2. per magnetogram
	-microfilm	8 weeks	\$10. /100 feet roll; minimum charge \$10.
One-minute digital data on magnetic tape	-1 minute digital data, no baseline control	1 month	\$35. for first file which includes cost of tape; \$15. for each additional file
	-1 minute digital data reduced to absolute standard	4 to 5 months	price as above
Hourly mean values and ranges (paper copy)	-provisional hourly values from one-minute data without baseline control	3 weeks	\$10. per data month; minimum charge \$10.
	-final hourly values and hourly ranges with baseline control	8 to 13 weeks	\$10. per data month; minimum charge \$10.
	-monthly and annual means with baseline control	3 months after year-end	\$0.25 per photocopy.
Hourly mean values and ranges (magnetic tape)	-hourly-mean values for values for Agincourt and Meanook from 1932 to 1966 with baseline control		\$60. per station (includes tape)
	-hourly mean values from 1967 on		\$35. for first file which includes cost of tape; \$15. for each additional file.



Table 3. Canadian Observatory Data Services and Costs (Continued)

<u>Type of Data</u>	<u>Description</u>	<u>Time Lag</u>	<u>Cost</u>
	-hourly ranges from 1967 on except for Meanook, Victoria, Ottawa, Agincourt and St. John's		as above
K-indices	-for Meanook, Victoria, St. John's, Ottawa; available twice monthly	1 week	none
Annual Report for Magnetic Observatories		1 year after end of year	\$4.00 copy in Canada
Forecasts	-Four-week geomagnetic forecasts from Ottawa Observatory issued every three weeks		none
	-Follow-up summary of observed magnetic activity at Ottawa Observatory issued every three weeks		none
Rapid-run F chart	-variable time base digital F data in chart form; available on request from Ottawa Observatory		\$0.25 per photocopy page

Table 4. Temporary Magnetic Variation Stations

Station	Acronym	Geographic		Geomagnetic		Mag. Elements Recorded	Photometer Channels Recorded	Recorder System	Interval
		Lat. N	Long. E	Lat. N	Long. E				
Alaska Bay	ABC	76.2	240.6	79.1	255.4	XYZ		D	3 78-
Polk Bay	PLB	68.5	270.5	78.6	320.4	HDZ		D	6 77-
								R	7 78-
Black Sea	BLC	See Observatories					1	A	6 77-
Black Sea	BLT	62.5	268.1	72.9	321.9	HDZ		D	10 76-
								R	7 78-
Iskara Point	IKP	61.1	265.9	71.1	321.8	HDZ		A	7 72-
								D	10 76-
								R	7 78-
Port of Call	POC	See Observatories					2	D	1 79-
Port of Call	POC	57.7	265.8	67.8	323.0	HDZ		R	7 78-
Port of Call	POC	See Observatories						D	4 77-
Port of Call	POC	56.0	272.4	66.8	323.0	HDZ		A	6 77-
Port of Call	POC	66.4	265.3	66.2	323.4	HDZ		D	4 77-
								R	7 78-
Port of Call	POC	66.7	262.1	65.4	319.3	HDZ		A	11 69-
								D	10 76-
Port of Call	POC	66.7	265.3	64.0	324.4	EDZ		A	10 76-
								D	10 76-
								R	7 78-
Port of Call	POC	See Observatories						A	11 69-9 75
								A	10 69-11 71
								A	11 69-11 71
								A	6 72-12 74
								A	11 69-9 75

A = Analog (Cathode ray), D = Digital (Magnetic tape), R = Real-time (Satellite transmission),  
 P = Port of Call.

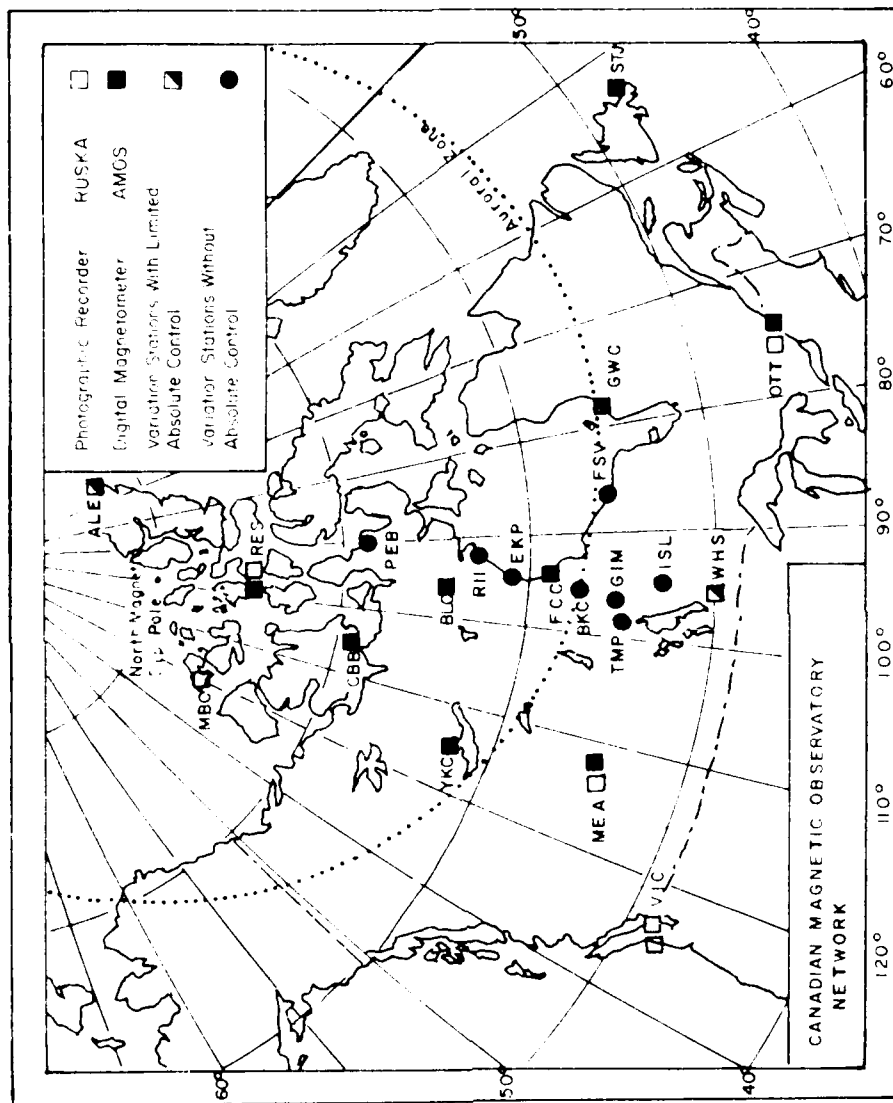


Figure 29. Magnetic Observatories and Variation Stations of the Earth Physics Branch (Courtesy of Earth Physics Branch)

### C. INSTITUTE OF GEOLOGICAL SCIENCES NETWORK

The magnetometer array operated in Europe by the Institute of Geological Sciences (IGS) evolved from an essentially N-S line of stations operated in the UK since 1970. This UK array extended from Lerwick (L. 3, 8) to Harland (L. 2, 5) with the addition of a station at Valentia, Eire, approximately  $10^{\circ}\text{W}$  of the main N-S line at L. 2, 6. This array was supplemented by the (approximately) conjugate pair of stations St. Anthony, Newfoundland (L. 4), and Holey Bay, Antarctica (L. 4), which are geomagnetically  $60^{\circ}\text{W}$  of the UK.

For IMS the magnetometers of the IGS array were upgraded by the inclusion of digital recording on cassettes and the addition of stations in Western Europe which were located to extend and intensify the network's coverage. The sites occupied in northern Europe were chosen to optimize analyses in conjunction with the planned schedule of GEOS I. Table 5 lists the stations used at various times since 1975 and Figure 30 shows a map of the stations currently being operated by IGS. The sites shown as squares have the prospect of continued operation for another 5 years. Also shown in Figure 30 are magnetometer arrays in Europe which can be used in conjunction with the IGS array to provide intensive ground coverage from the auroral zone to midlatitudes and over a 3 hour local time sector. Note that extension of the AFGL network eastward links well into the Eskdalemuir-Nurmijarvi link of the present IGS array. It is expected that this E-W profile will be extended by placing one of the two IGS magnetometers in the USSR at the same latitude and approximately  $15^{\circ}\text{E}$  of Nurmijarvi. It is also hoped to reoccupy a station in Southern Scandinavia halfway between Eskdalemuir and Nurmijarvi.

The IGS magnetometers use Rb sensors, and a system of backing off fields is employed to produce vector variation information. Raw data, without absolute control of baselines, is recorded as the NE and NW (geomagnetic) components of the horizontal field and Z. The three components are sampled simultaneously at 2-1/2 second intervals and the sensor frequencies recorded serially on cassette magnetic tape. Eight bits of data are recorded from each sensor. Depending on magnetic latitude the sensitivity in the range is set to 0.04 nT per bit and 0.1 nT per bit. The dynamic range is not restricted by the use of eight bits since a device is used to "prevent" scale jumps in the recording (as when all bits change from 11111111 to 00000000). This device improves the quality of directly recorded analog records and is useful as a flag in the use of digital data, allowing scale jumps to be identified and corrected for in data preparation. It is important to note that the dynamic capability of the magnetometers is limited only in times of extremely rapid large field depressions and that the frequency response is flat from 100 mHz to DC. Thus, although the instruments were designed primarily

for pulsation work, the ability to see simultaneous background field movements is retained. A conversion of the equipment from Rb to fluxgate sensors is expected to take place over the next few years but the recording format and basic specification will remain the same.<sup>26</sup>

Cassetts are sent by post to Edinburgh where they are transcribed to machine tape. Transcription makes no corrections to the data and master tapes are written at 1600 bpi in binary on nine-track tape. The cassette contains 3 days data from one station and is transcribed in 5 minutes. A logical system of filing consecutive cassettes from each station on separate master tapes is used and software for data retrieval is available. A 2400 ft. station tape contains 6 months data from a single magnetometer site. An analog record is made for each cassette (for each station). This is used in fault diagnosis as well as for "quick look" selection of events, etc. Figure 31 shows a section of the quick look record with traces being NE, NW, and Z from top to bottom. Figure 32 shows the same event recalled from master tape with the scale jump removed (automatically) and the records rotated to the conventional H, D, and Z.

Data can be made available in prepared form (for example, as flat bed plots using selected filters), in part analyzed form (plots plus spectra, cross spectra, polarization, etc.), or as digital data.<sup>27</sup> For users who do not have the IGS software for data preparation the data can be provided in ASCII on nine-track tape (300 or 1600 bpi). The format of digital data is shown in Table 6. Data of this type have been corrected for scale jumps and an arbitrary base line is added.

Inquiries for copies of data or proposals for cooperative research projects using the data from this array should be addressed to: Dr. W. F. Stuart, Geomagnetism Unit, Institute of Geological Sciences, Murchison House, West Mains Road, Edinburgh, EH9 3LA. Telephone 031-667-1000, Telex 727 343.

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26. Riddick, J.C., Brown, J., and Forbes, A.J. (1975) A Low Power Movable Observatory Unit for Magnetometer Array Applications, Institute of Geological Sciences, Geomagnetism Unit, Report No. 17, Edinburgh, U.K.
  27. Mills, P.M., Dyson, K., Green, C.A., and Stuart, W.F. (19--) The Data Transcription and Retrieval System Use for Cassette Recording of the IGS Rubidium Magnetometers, Institute of Geological Sciences, Geomagnetism Unit, Report No. 20, Edinburgh, U.K.

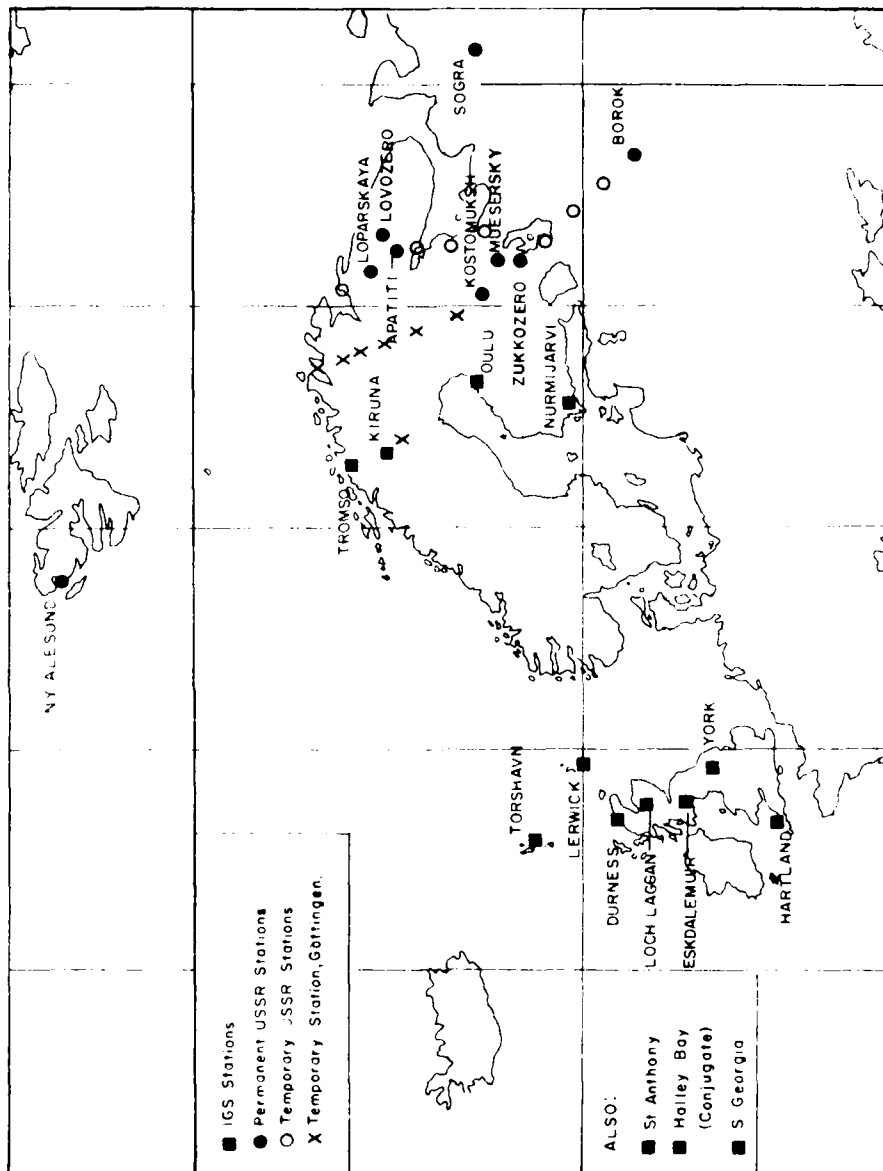


Figure 30. IGS Network Stations (Courtesy of IGS)

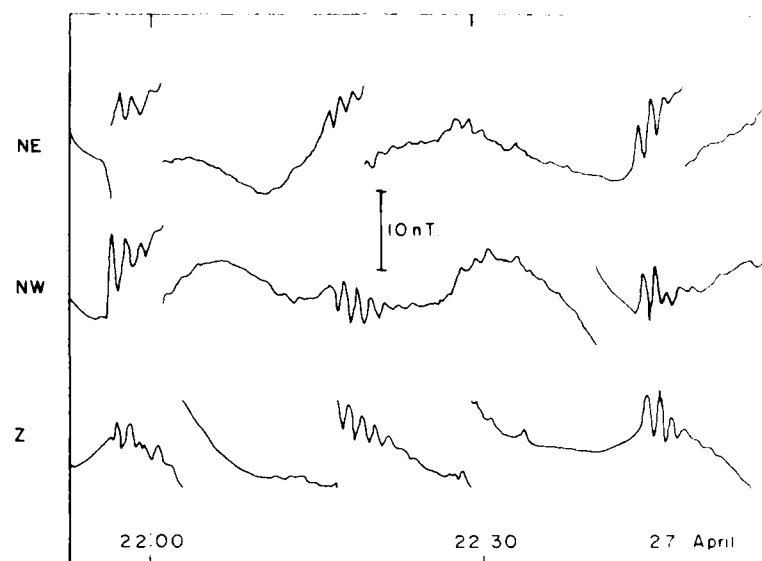


Figure 31. Quick Look Record Section (Courtesy of IGS)

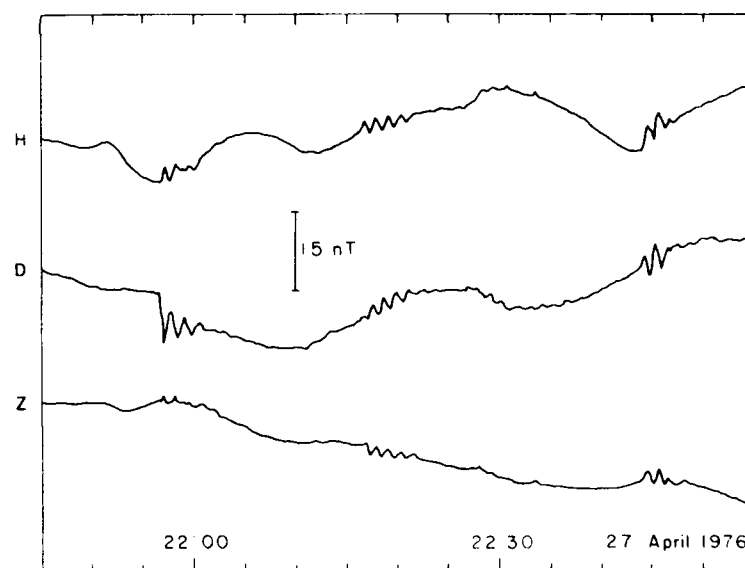


Figure 32. Final Format Per Master Tape (Courtesy of IGS)

Table 5. IGS Magnetometer Stations

Station	Coordinates				Period
	Geographic		Geomagnetic		
Lerwick	60°08	358°49	62.53	88.97	1976 Jan-
Durness	58°35	351°14	61.83	84.07	1977 Oct-
Loch Laggan	57°24	355°48	60.27	83.20	1976 Feb-May, 77-
Earlyburn	55°42	356°48	55.88	83.48	1976 Jan-77 June
Eskdalemuir	55°19	356°48	58.49	82.23	1976 Feb-
York	53°58	358°55	56.79	84.51	1976 Jan-
Cambridge	52°15	0°03	54.93	84.59	1977 Sept
Valentia	51°56	349°45	56.70	73.76	1976 Jan-77 March
Hartland	50°59	355°31	54.68	79.28	1976 Jan-77 Apr
Tromsø	69°40	18°57	67.03	117.13	1976 Sept-
Kiruna	67°50	20°25	65.15	115.95	1976 Sept-
Oulu	65°05	25°52	61.83	117.26	1977 June
Nurmijarvi	60°31	24°39	57.78	112.88	1976 Sept
Kvistaberg	59°30	17°38	58.19	106.02	1976 Sept-77 June
Arendal	58°18	8°38	59.02	97.05	1976 Sept-77 June
St. Anthony	57°04	308°39	62.62	18.34	1976 July
Leivogur	64°11	338°18	70.28	71.57	1977 Apr-76 Aug
Eidar	65°22	341°03	70.80	76.33	1977 Apr-78 Aug
Torshavn	62°02	353°41	65.39	85.19	1977 Aug
King Edward Point	-54°17	333°24	-44.04	25.89	1976 July-
Halley Bay	-75°31	323°31	-65.60	24.09	1976 July-



Table 6. IGS Data Tapes for Special Intervals

9 tracks  
 800 or 1600 BPI  
 Odd parity  
 ASCII  
 Block length        3960    (10-min data)  
 Lines per block     30        (3 lines/minute)  
 Bytes per line      132      (24 values at 2-1/2 sec intervals)

Line Structure

Byte position  
   1-2       Station identifier  
   3-4       Year (last 2 digits)  
   5-7       Day (000-365)  
   8-9       Hour (00-23)  
 10-11      Minute (00-59)  
   12       Component (H, D or Z)  
 13-17      }  
 13-17      } 24 component field values  
 13-17      } in 1/10 nT units  
 128-132    } (50000 added)

Each line can be read under Fortran using a decode statement  
 Format A2, I2, I3, 2I2, A1, 24 F.5.1

The format used is a quasi-1 minute format with 24 component values to a line. These field values were recorded at 2-1/2 second intervals during the course of the minute given in byte position 10-11.

#### D. U.S. - CANADIAN IMS NETWORK

The U.S. - Canadian IMS ground magnetometer network consists of 25 stations equipped with flux gate magnetometers, digital recording, and interface units to transmit data to the NOAA Space Environment Laboratory. A radio link via the NASA/NOAA, SMS/GOES geostationary weather satellite is utilized for data from the network and a 26th station located at the SEL, Boulder, Colorado, inputs directly. The satellite transmission relay (STR) stations are located in three high-latitude and one midlatitude chain and include several stations that are normally part of such networks as the Alaskan (Akasofu), the Canadian (Rostoker and Walker), and USGS (Wood) installations.

The high-latitude chains consist of the Alaskan Chain along the 260°E magnetic meridian through College, Alaska, extending to the vicinity of the invariant pole; the Fort Churchill chain along the 326°E magnetic meridian through Fort Churchill, Manitoba; and an east-west chain along the auroral oval linking the above two chains. Figure 33 illustrates the location of these chains and Figure 34 shows the midlatitude IMS network. A listing of all 26 network stations is provided in Table 7.

In addition, two more Alaskan stations, Isaacson and Eureka, and a midlatitude station, Guam, collect data on site on magnetic tape. Data from these sites which are out of range for satellite relay are then mailed to Boulder for processing.

The magnetometers used by the three main Canadian nets and by the USGS are generally EDA Instruments Inc. fluxgate units with models FM-100 and FM-100C predominant. Not all EDA units operate alike; some are operated in a closed-loop mode with automatic feed back and some need manual setting. External standard cells are generally used for reference at each station with sensors mounted in a block of lucite glass, orthogonal to  $1-2^\circ$ , and passive temperature control obtained through deep burial. The midlatitude chain magnetometers are set such that an output of  $\pm 10$  volts corresponds to  $\pm 1000$  gamma and high-latitude outputs of  $\pm 10$  volts equalling  $\pm 4000$   $\gamma$  are common. These magnetometers, under control of a microprocessor in a data logger, sample once per second, then take and store 10-second average values.

This stored data is then transmitted from the automatic stations to one of the NASA/NOAA, SMS/GOES geostationary weather satellites in 12-minute blocks. It is then relayed to a receiving system at Wallops Island, Virginia, and telemetered to the World Weather Building at Marlow Heights, Maryland. The data is then sent over a dedicated telephone line to Boulder, Colorado, where a system of minicomputers (SEL/DADS) records and displays the data and prepares tapes which are sent to the Environmental Data Information Service (EDIS) for dissemination.

The data is available to the scientific community in several formats:

1. "Stackplots" (see Figure 35) of the data for each component and for each chain are prepared from one-minute averaged data. These plots are available on microfilm for month-long data intervals.

2. The 1-minute averaged digital data itself is available on magnetic tape, 1 month at a time.

3. Ten-second resolution data are available on magnetic tape, a few days at a time.

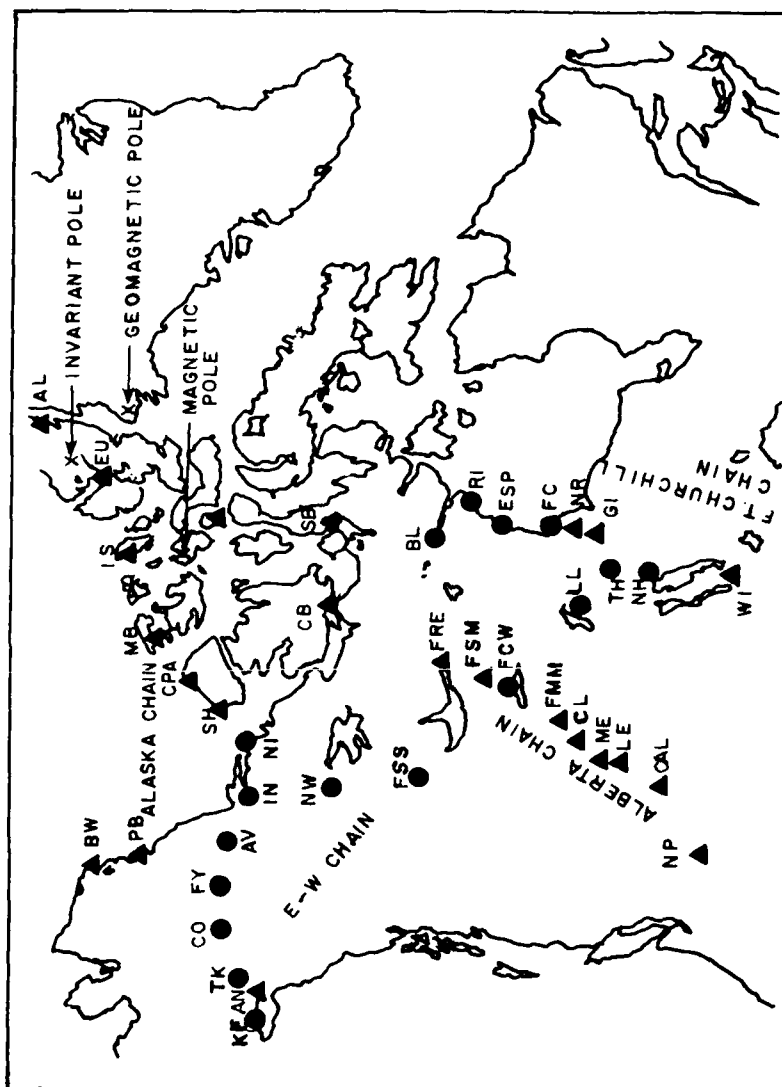
To obtain any of these data, contact Joe H. Allen, EDIS World Data Center-A, Boulder, CO 80303, Telephone (303) 499-1000, X6501.<sup>28</sup>

At NOAA, the primary use of the data is to generate the substorm catalog which is compiled by Joe Sutorik and published weekly in the Preliminary Report and Forecast of Solar Geophysical Data, a product of the Space Environment Services Center of NOAA's Space Environment Laboratory. This catalog provides the date, onset time, and direction from Boulder (east, west, or centered) of each substorm clearly identifiable by inspecting the chains stackplots. This information is useful not only to researchers who wish to select data intervals for study, but also to operational personnel looking for explanations for "malfunctioning" equipment.

SESC also uses the midlatitude IMS data to provide near real-time estimates of the DST of magnetic storms.

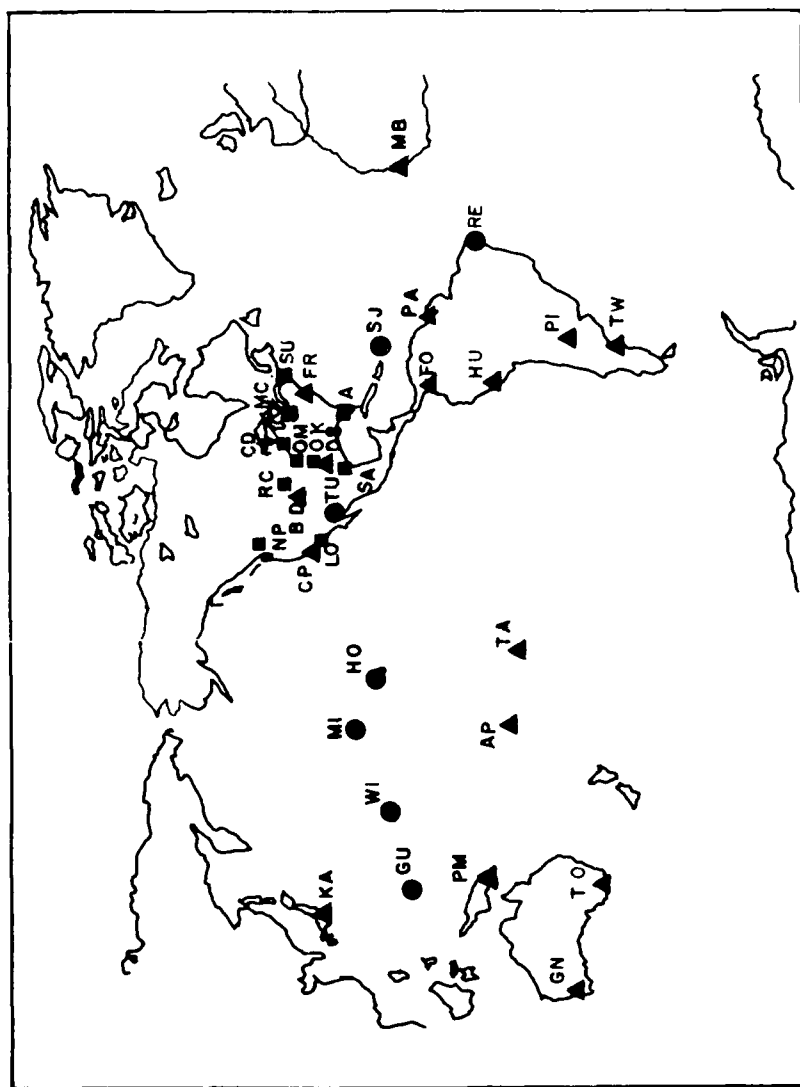
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- - SATELLITE RELAY, IMS NETWORK
- ▲ - ON-SITE RECORDING

Figure 33. North American High-Latitude Magnetometer Network for IMS (Courtesy of NOAA)



●-- SATELLITE RELAY, IMS NETWORK

▲-- ON SITE RECORDING

Figure 34. North American Midlatitude Magnetometer Network for IMS (Courtesy of NOAA)

MIDLATITUDE CHAIN H-TRACE DAY 81- 3/22/79

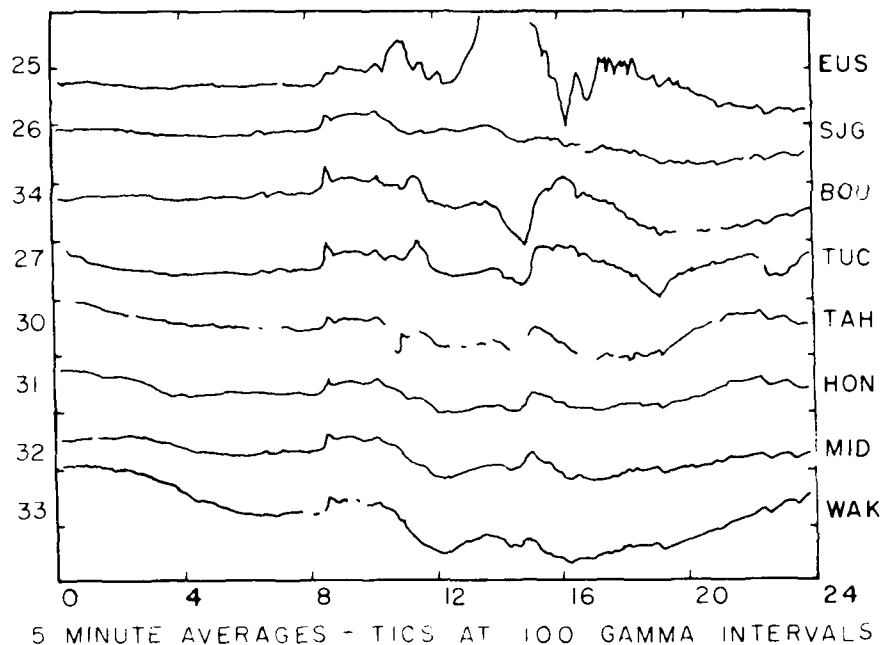


Figure 35. Midlatitude Chain H-Trace Day 81 (Courtesy of NOAA)

Table 7. U.S.-Canadian IMS Magnetometer Network

<u>Alaska Chain</u>	<u>Fort Churchill Chain</u>
Johnson Point	Pelly Bay
Sachs Harbour	Rankin Inlet
Cape Parry	Eskimo Point
Inuvik	Back
Arctic Village	Gillam
Fort Yukon	Island Lake
College	
Talkeetna	
<u>East-West Chain</u>	<u>Midlatitude Chain</u>
Norman Wells	Eusebio
Fort Simpson	San Juan
Lynn Lake	Boulder
Fort Smith	Tucson
	Tahiti
	Honolulu
	Midway Island
	Wake Island

## E. AIR WEATHER SERVICE NETWORK

Air Weather Service (AWS), through its operational forecast center at the Air Force Global Weather Central (AFGWC), provides round-the-clock forecasts and specifications of the space environment. Broadscale and mission tailored products are provided to a wide variety of DoD customers affected by the solar-terrestrial environment. A more general and wider range of customer support is achieved through a co-operative effort with NOAA's Space Environmental Laboratory in Boulder, Colorado.

AWS currently receives real-time observations from five magnetometer sites. These sites are located at College, Alaska; Loring, Maine; Goose Bay, Labrador; Boulder, Colorado; and Thule, Greenland. Schonstedt HSM-1 fluxgate magnetometers are utilized with two components set to magnetic north (at high and low sensitivities) and a third in the vertical (Z) direction. Strip chart recording is utilized with the neutralizing field control and recorder scale factor set to insure that the low sensitivity channel will be on scale for events of magnitude  $K_p = 9$ . Regular observations and readings are made every 90 minutes and maximum and minimum values transmitted in the Astrophysical Telecommunications Network (ATN) not later than 10 minutes thereafter. Data from the first four sites are used to develop pseudo 90 minute and three hourly  $a_p$  values. The three hourly values are combined to produce an  $A_p$  calculation. Thule observations, taken in the polar cap region, are not used in these calculations. A significant improvement in global coverage will be achieved shortly with the addition of a new site at Upper Heyford, England. This addition will make the real-time coverage comparable to the delayed Gottingen Observatory calculations. Presently, the loss of one or two sites due to communication or maintenance problems severely degrades our ability to specify the pseudo  $a_p$ . Addition of real-time data from the AFGC Magnetometer Network in late 1979 will greatly improve the quality and reliability of the AWS magnetometer products.

Station	Geomagnetic Coordinates		Geographic Coordinates	
	<u>N Lat</u>	<u>E Lat</u>	<u>N Lat</u>	<u>E Lat</u>
Holton AFB, Alaska	64.6	257.5	64.7	147.0
Thule AB, Greenland	88.0	5.7	76.5	68.8
Goose AB, Labrador	60.1	11.9	53.3	60.4
Loring AFB, Maine	58.1	1.5	46.9	67.9

Contact for additional information is: Major Vernon G. Patterson, AFGWC TSIS, Offutt AFB, NE 68111; Autovon 271-3477.

## F. SCANDANAVIAN IMS NETWORK

As a part of its IMS program the University of Munster has set up a large network of magnetometers in the Scandinavian countries. The work has been done in cooperation with scientists from following institutions: Geophysics Laboratory, Aarhus University; Finnish Meteorological Institute, Helsinki; Kirema Geophysical Institute; Sodanmyla Geophysical Observatory; Finnish Academy of Science and Letters; Department of Plasmas and Physics, Institute of Technology, Stockholm; Auroral Observatory, Trurso; and Uppsala Ionospheric Observatory. A total of 32 sites were selected (see Figure 36). The magnetometers installed at these sites are three-component improved Gough-Reitzel "posthold" units recording photographically on 35 mm film, one sample per 10 sec. The resolution is  $\pm 2$  nT with a film scale of about 45 nT/mm. The stations are coordinated with several regular magnetic observations in Scandinavia and the Kertz and Maurer chain of digital magnetometers (profile #5 in the Figure 36). A combined listing is given in Table 8.

The records will be used to perform detailed analysis of spatial and temporal behavior of high-latitude ionospheric current systems including field-aligned currents in co-operation with other groups in the area operating all-sky cameras, riometers, auroral radar, etc. The N-S and E-W structures of geomagnetic variations will be studied with periods down to 1 min. Analog traces will be digitized for selected periods and such data will be available for co-operative analysis. For other times film copies of the original magnetograms will be available at request in reasonable quantities. For more detailed information please contact Prof. J. Untiedt, Institut für Geophysik, Universität Munster Gievenbecker Weg 61, D-4400 Munster F.R.G. Data from the Braunschweig IMS magnetometer chain (profile #5) has been reported to be available with two different time resolutions of 10 sec and 30 sec per sample (Figure 31). Please contact Dr. H. Maurer 33 Braunschweig, Mendelssohnstrasse 1, F.R.G.



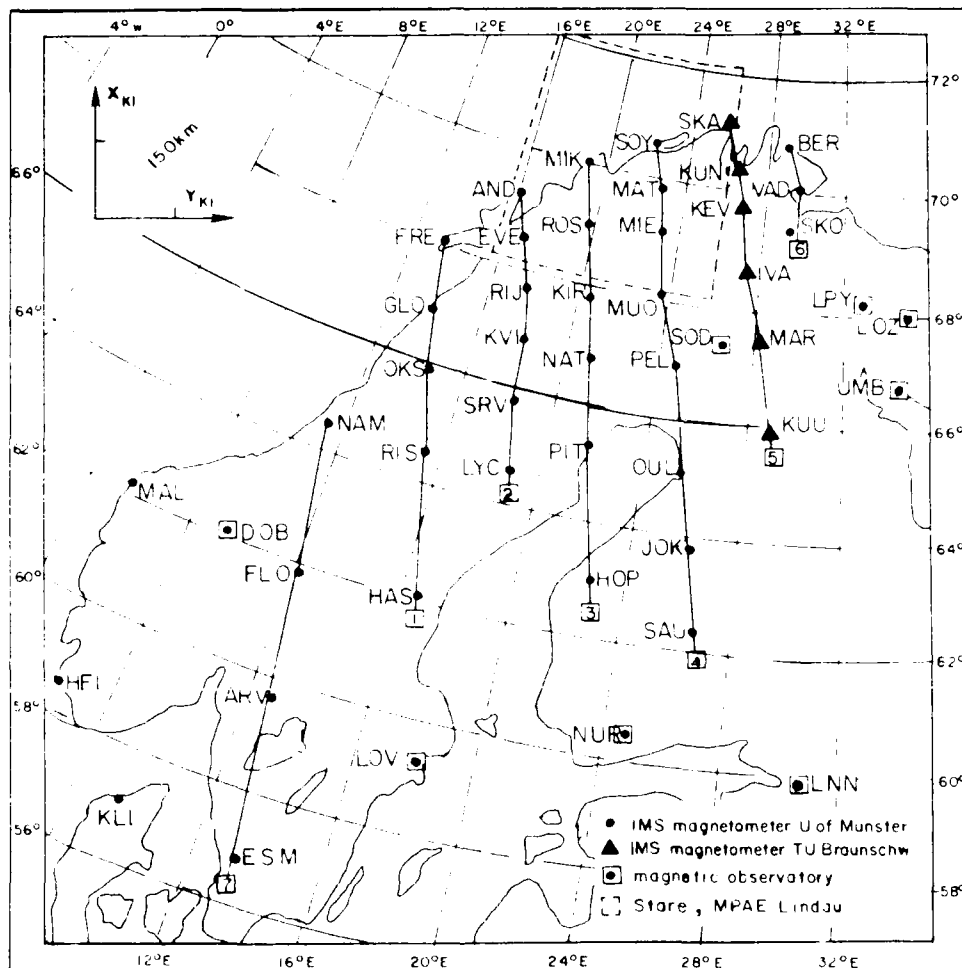


Figure 36. Scandinavian IMS Network (Courtesy W. Baumjohann)

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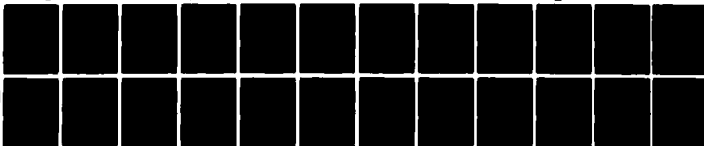
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Table 8. Scandanavian IMS Network

Profile	Station Code	Station Name	Geogr. Lat.	Geogr. Long. E
1	FRE	Fredvang	68.08	13.17
	GLO	Glomfjord	66.90	13.58
	OKS	Okstindan	65.90	14.27
	RIS	Risede	64.50	15.13
	HAS	Hassela	62.07	16.50
2	AND	Andenes	69.30	16.02
	EVE	Evenes	68.58	16.77
	RIJ	Ritsemjokk	67.70	17.50
	DVI	Kvikkjokk	66.90	17.92
	SRV	Storavann	65.78	18.18
	LYC	Lycksele	64.57	18.68
3	MIK	Mikkelvik	70.07	19.03
	ROS	Rostadalen	68.97	19.67
	KIR	Kiruna	67.83	20.42
	NAT	Nattavara	66.75	21.00
	PIT	Pitea	65.25	21.58
	HOP	Hoopaka	63.01	22.56
4	SOK	Soroya	70.60	19.03
	MAT	Mattisdalen	69.85	22.92
	MIE	Mieron	69.12	23.27
	MUO	Muonio	68.03	23.57
	PEL	Pello	66.85	24.73
	OUL	Oulu	65.10	25.48
	JOK	Jokikyla/Pyhasalmi	63.77	26.13
	SAU	Sauvamaki/Hankasalmi	62.30	26.65
5	KEV	Kevo	69.52	27.00
	IVA	Ivalo	68.40	27.40
	MAR	Martti	67.28	28.20
	KUU	Kuusamo	65.57	29.15
6	BER	Berlevag	70.85	29.13
	VAD	Vadso	70.10	29.39
	SKO	Skogfoss	69.37	29.42
7	NAM	Namsos	64.45	11.13
	FLO	Flotingen	61.88	12.23
	ARV	Arvika	59.60	12.60
	ESM	Esmared	56.74	13.22
	MAL	Maloy	62.18	5.10
	HEL	Hellvik/Egersund	58.52	5.77
	KLI	Klim	57.12	9.17

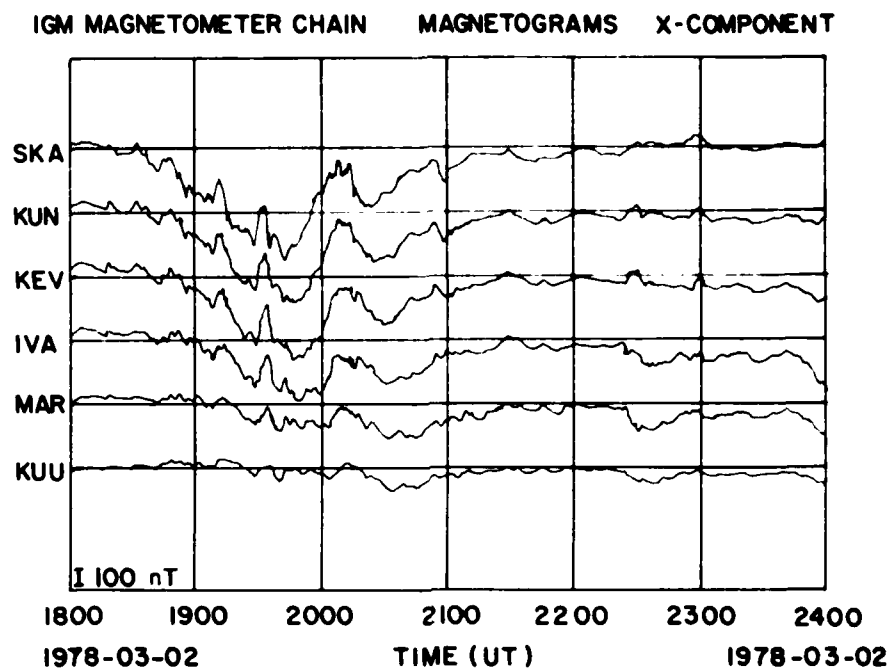


Figure 37. IGM Magnetometer Chain Magnetograms X Component  
(Courtesy H. Maurer)

### C. UNIVERSITY OF ALBERTA NETWORK

The University of Alberta operates a line of four magnetometers extending northward along  $\sim 300^{\circ}\text{E}$  from Leduc, Alberta ( $60.60^{\circ}\text{N}$ ), which connects to an east-west line of four magnetometers stretching along approximately  $67.5^{\circ}\text{N}$  from Uranium City, Saskatchewan, to Fort Providence, N.W.T. Fort Smith is a station common to both the meridian and east-west lines. Table 9 and Figure 38 gives coordinates and location respectively. Each station is equipped with a three-component fluxgate magnetometer recording H, D, and Z at a sample rate of one sample per component every 2.56 seconds. Timing is accurate to  $\pm 0.1$  sec and amplitudes are accurate to  $\pm 1$  nT over a full-scale range of 1000 nT. Aliasing filters remove power in the frequency band  $f > 0.3$  Hz. Riometers operating at 30 mHz functioned intermittently at all the sites at various times since installation of the stations was effected in the late summer of 1976.

The University of Alberta east-west line provides coverage over  $\sim 12^{\circ}$  of longitude, but this coverage can be extended by utilizing data from Fort Simpson (to the west) and Lynn Lake (to the east) which were also in operation during the IMS. The meridian line portion of the University of Alberta array can be extended and supplemented by the addition of data from stations to the north (Resolute Bay, Cambridge Bay, and Yellowknife), within the array (Meanook), and to the south of the line (Newport). This results in a meridian line with coverage extending from  $\sim 55^{\circ}\text{N}$  to  $\sim 83^{\circ}\text{N}$  geomagnetic latitude.

Data from the array are maintained on nine track magnetic tapes at the University of Alberta. Archive tapes providing 1 minute averaged values of H, D, and Z at each station have been provided to World Data Center A. Small suites of original data can be provided to Canadian experimenters at no cost.

Principal Investigator - Dr. Gordon Rostoker  
Institute of Earth and Planetary  
Physics and the Department of Physics  
University of Alberta  
Edmonton, Alberta T6G 2J1  
(403) 432-3713

Collaborators - Dr. John V. Olson  
Dr. John C. Samson  
(address as above)

Table 9. University of Alberta Network

Site	Geographic		Geomagnetic		Date Activated (1976)
	Lat. (°N)	Long. (°E)	Lat. (°N)	Long. (°E)	
Fort Providence (PROV)	61.3	242.4	67.5	292.0	Aug 11
Hay River (HAYR)	60.8	244.1	67.3	294.3	Aug 10
Uranium City (URAN)	59.6	251.5	67.4	304.3	July 16
Fort Smith (SMIT)	60.0	248.0	67.3	300.0	July 11
Fort Chipewyan (FTCH)	58.8	248.0	66.3	303.1	July 17
Fort McMurray (MCMU)	56.7	248.8	67.2	303.5	July 17
Leduc (LEDU)	53.3	246.5	60.6	302.9	July 10

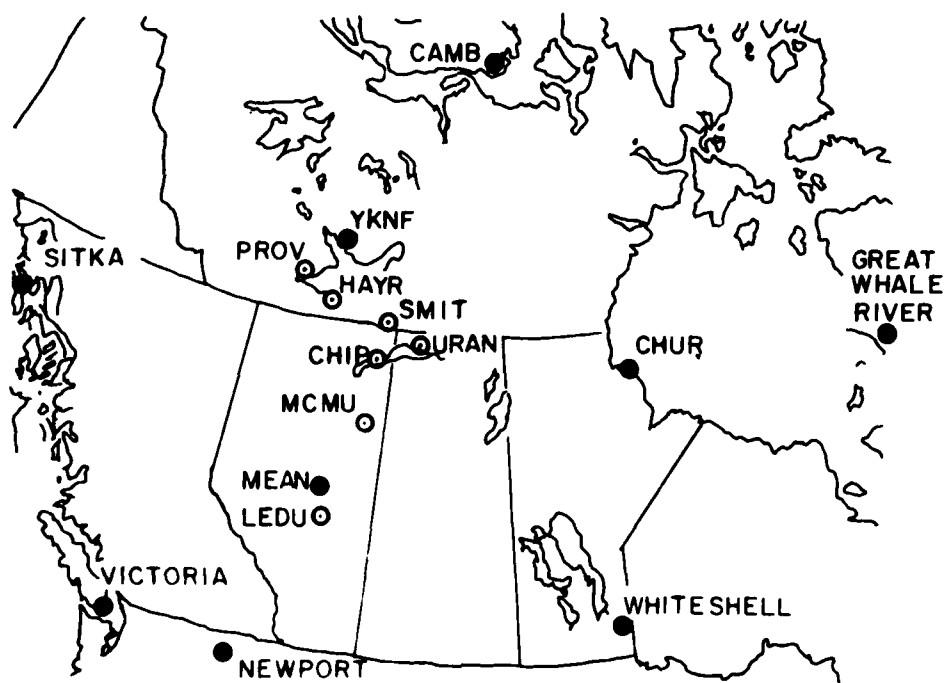


Figure 38. University of Alberta Magnetometer Array  
(Courtesy of University of Alberta)

## H. ALASKAN NETWORK

The Geophysical Institute of the University of Alaska operates a chain of stations extending from the Pacific coast to the vicinity of the invariant pole approximately along the  $260^{\circ}\text{E}$  geomagnetic meridian. This chain includes the Canadian magnetic observatory at Mould Bay and a USGS observatory at College. The USGS observatory at Barrow, situated to the west of the meridian chain is an additional important auroral zone station. Table 10 lists pertinent information; stations designated with an asterisk are part of the U.S. -Canadian IMS magnetometer network. Details of operation and data availability are given in the section presented by J. Joselyn. Figure 39 shows the location of the Alaskan chain stations. Data from the non-satellite relay stations are available from WDC-A in Boulder as 1 month tapes with 5 minute averages.

Contact is: Dr. S. -I. Akasofu  
Geophysical Institute  
C. T. Elvey Bldg.  
University of Alaska  
Fairbanks, AK 99701  
Phone: (907) 479-7367

Table 10. Alaskan Chain Stations

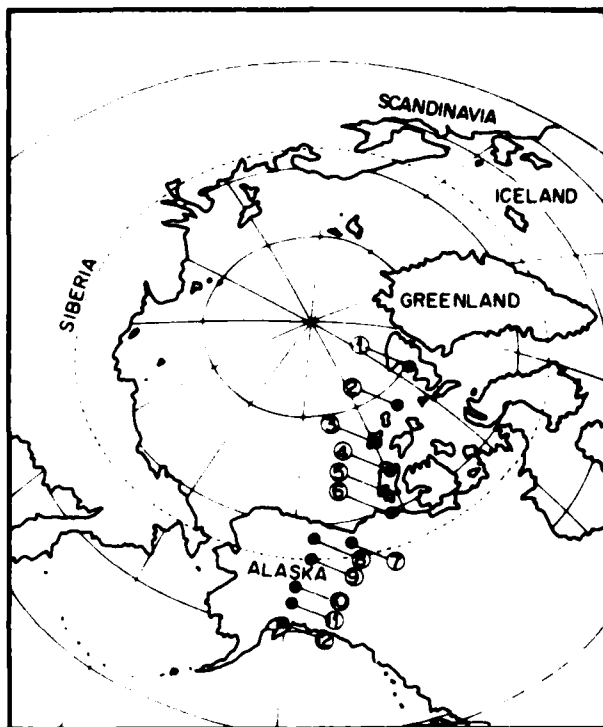
Location	Geographic		Geomagnetic		Operating Organization
	Lat. N	Long. W	Lat. N	Long. E	
Eureka	80 <sup>0</sup>	85 <sup>0</sup> 75			UAI.
Isachsen	78.80	104			UAI.
Johnson Point*					UAI.
Mould Bay†	76.2	240.6	79.1	255.4	EMR
Sachs Harbor*	72	125	75.27	266.40	UAI.
Cape Perry*	70.20	124.70			UAI.
Inuvik*	68.25	133.30	70.58	266.40	UAI.
Arctic Village*	68.13	145.57	67.88	254.52	UAI.
Fort Yukon*	66.57	145.28	66.62	256.80	UAI.
Poker Flat	65.13	147.48	65.12	257.55	UAI.
College*†	64.88	148.05	64.60	256.30	GS UAI.
Talkeetna*	63.30	150.10	61.88	256.95	UAI.

\* U.S. -Canadian IMS Magnetometer Network Station.

† Energy, Mines, and Resources Canada Magnetic Observatory; magnetometer with analog readout.

† U.S. Geological Survey Magnetic Observatory.





IMS Alaska Meridian  
Chain of  
Geophysical Observatories

	Invariant Latitude
1 EUREKA	89°
2 ISACHSEN	86°
3 MOULD BAY	81°
4 JOHNSON POINT	78°
5 SACHS HARBOUR	76°
6 CAPE PARRY	74°
7 INUVIK	71°
8 ARCTIC VILLAGE	69°
9 FORT YUKON	67°
10 FAIRBANKS	65°
11 TALKEETNA	62°
12 ANCHORAGE	61°

Figure 39. IMS Alaska Meridian Chain  
(Courtesy of University of Alaska)

## I. INDIAN NETWORK

A total of 10 magnetic observatories are being operated in India, seven of them by the Indian Institute of Geomagnetism, Colaba, Bombay, and one each by the Indian Institute of Astrophysics, Kodaikanal; National Geophysical Research Institute, Hyderabad; and Geodetic Research Branch, Survey of India, Dehra Dun. The geographic and geomagnetic co-ordinates of the observatories together with the year from which they have been functioning, type of equipment used, and approximate value of D, I, H, Z, and F are given in Table 11.

Apart from standard magnetic variometers two of the observatories of Indian Institute of Geomagnetism, those at Alibag and Trivandrum, are equipped with locally fabricated micropulsation stations. At four of the magnetic observatories of the Indian Institute of Geomagnetism the absolute determination of horizontal and vertical intensities is made by vector proton magnetometers. The Institute has also fabricated a receiving and recording station on Whistlers which is shortly proposed to be installed at Srinagar in Kashmir.

For additional information please contact:

Dr. B. N. Bhargwa  
Director  
Indian Institute of Geomagnetism  
Colaba, Bombay, India 400-005

Table 11. Indian Network

Station	Geographic		Dipole		Function- ing from	Type of Variometers	Organi- zation*	D	Approximate Values of			
	Lat.	Long.	Lat.	Long.					I	H	Z	F
Gulmarg	34°03'N	74°24'E	24°5'N	147°2	1977	La Cour	IIG	1.5	51.0	31000	nT 40050	nT 50700 <sup>†</sup>
Sabhawala	30 22 N	77 48 E	20.8N	149.8	1964	Askania La Cour	SOI	0.5	45.3	34050	34450	48430
Jaipur <sup>†</sup>	26 55 N	75 48 E	17.3N	147.4	1975	IZMIRAN IV	IIG	0.0	39.4	36000	29550	46570
Shillong	25 34 N	91 53 E	14.6N	162.4	1975	La Cour	IIG	-0.8	36.5	37770	37950	47000 <sup>‡</sup>
Ujjain <sup>†</sup>	23 11 N	75 47 E	13.5N	147.0	1975	IZMIRAN IV	IIG	-0.7	32.7	37350	24200	44500
Alibag	18 38 N	72 52 E	9.5N	143.6	1904	Watson La Cour	IIG	-0.8	24.2	38600	17400	42350
Hyderabad	17 25 N	78 33 E	7.6N	148.9	1965	IZMIRAN II La Cour	NGRI	-1.6	20.5	39900	14900	42600
Annamalainagar	11 22 N	79 41 E	1.4N	149.4	1937	Askania	IIG	-2.7	5.4	40500	3800	40670
Kodaikanal	10 14 N	77 28 E	0.6N	147.1	1949	La Cour Watson	IIA	-2.5	3.1	39400	2100	39450
Trivandrum	8 29 N	76 57 E	1.2S	146.4	1957	Askania IZMIRAN II	IIG	-2.8	-0.9	39950	-650	39960

\* IIG: Indian Institute of Geomagnetism, Colaba, Bombay-5.

IIA: Indian Institute of Astrophysics, Kodaikanal-3.

NGRI: National Geophysical Research Institute, Hyderabad-7.

SOL: Geodetic &amp; Research Branch, Survey of India, Dehra Dun, U. P.

† Temporary stations.

‡ Values derived from IGRF.

## J. NATIONAL INSTITUTE OF POLAR RESEARCH NETWORK

The National Institute of Polar Research has established a network of stations along the 80th geomagnetic meridian in Antarctic and a conjugate point station at Husafell, Iceland. Three of the southern sites, Syowa, Mizuho, (manned) and A1, (unmanned) are operating with M2 (unmanned) scheduled for installation in September 1979.

Instrumentation of the manned sites includes fluxgate magnetometer, induction magnetometer, 30 mHz riometer, VLF wideband receiver, and auroral TV camera. The unmanned stations will include fluxgate magnetometer, induction magnetometer, and 30 mHz riometer. The location of these stations is shown in Figure 40 and their coordinates given in Table 12. The conjugate stations, Husafell and Syowa, occupy areas corresponding to the northern and southern hemisphere feet of the magnetic field lines through GEOS 1.

For additional information please contact:

Dr. Hiroshi Fukunishi  
National Institute of Polar Research  
9-10, Kaga 1-Chome, Itabashi-Ku  
Tokyo 173, Japan  
Telephone (03) 962-4711

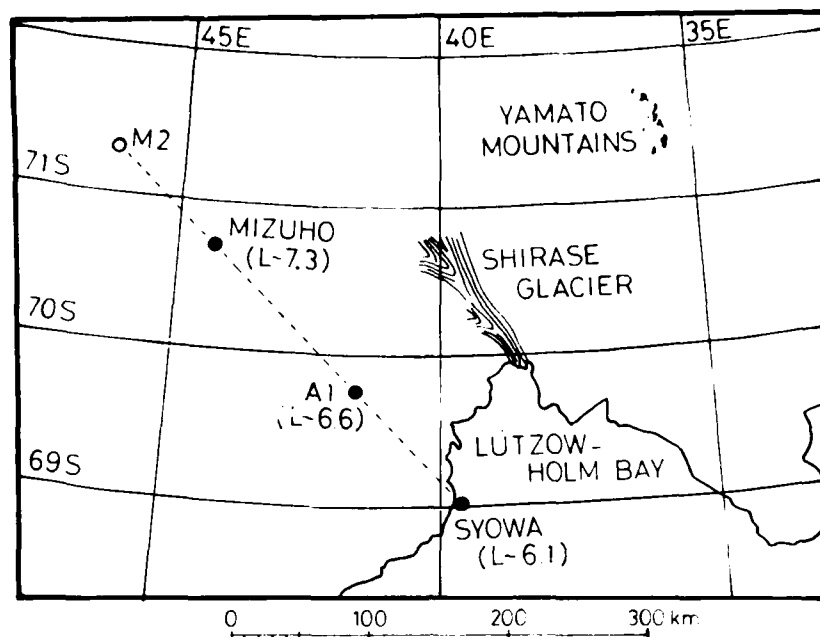


Figure 40. National Institute of Polar Research Magnetometer Array  
(Courtesy of NIPR Japan)

Table 12. National Institute of Polar Research Network

Station Name	Geographic		Geomagnetic	
	Lat.	Long.	Lat.	Long.
Syowa	69.03°S	39.6°E	-70.03°	79.39°
A1 (Unmanned Station)	69.8°S	41.6°E	-71.04°	79.87°
Mizuho	70.7°S	44.33°W	-72.32°	80.62°
Husafell (Iceland)	64.7°N	20.9°W	70.19°	74.24°

## K. UNITED STATES GEOLOGICAL SURVEY NETWORK

The USGS operates magnetic observatories as tabulated in Table 13. An additional observatory, Honolulu, is operated by the NOAA Weather Service but the data is processed by the USGS in its normal format. The stations at Boulder, Sitka, Tucson, College, and Barrow are operating digital fluxgate-proton systems. The first four employ a sample rate of one complete set every 10 seconds except Barrow which is on a 20-second cycle. The units at College, San Juan, and Tucson also function as a part of the U.S. -Canadian IMS Magnetometer Network utilizing satellite data relays. The 1979-1980 program plans include the conversion of all stations to the digital fluxgate-proton system and the addition of two new unmanned observatories, one in California at the base of the San Joaquin range and one in either southern Texas or northern Florida. The program also calls for the replacement of the shared large computer facility with a dedicated mini-computer with full station dial-up and check-out functions. The new computer will also prepare individual monthly observatory publications containing mean hourly values and station magnetograms. Base lines will be checked periodically depending on the stability of the individual stations. Barrow is currently being checked only every 4 to 6 weeks with excellent results, the major limitation being temperature stability. Regional conductivity studies will also be completed as part of each new observatory installation.

The repeat station survey program used as basic input for preparation of magnetic charts is also active. About 150 out of 250 such sites in the U.S. will be occupied in 1979. Similarly about 25 out of 50 Alaskan sites will be occupied in 1979-1980 and as many as 10 South Pacific sites, logistics permitting. Additional sites in all areas may be occupied over the next several years to provide special support to the MAGSAT program.

Contact for additional information:

John D. Wood  
USGS  
Branch of Electromagnetism and Geomagnetism  
Denver Federal Center, MS964  
Denver, CO 80225  
Telephone (303) 234-5458

Table 13. United States Geological Survey Network

Location	Geographic		Geomagnetic	
	Lat. N	Long. W	Lat. N	Long. E
Barrow	71.30	156.75	68.64	241.55
College	64.88	148.05	64.60	256.30
Sitka	57.07	135.33	60.09	275.86
Newport	48.26	116.99	55.15	30.76
Boulder	40.08	105.14	49.0	316.5
Fredericksburg	38.20	77.37	49.54	350.42
Tucson	32.25	110.83	40.48	312.72
San Juan	18.12	66.15	29.57	3.63
Guam	13.58	215.13	4.04	213.35
Honolulu	21.32	158.00	21.17	266.99

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## Appendix A

### A List of Potential Events for Special Study

The intervals studied at the IMS Workshop held in Tokyo, March 1979.

During each of these intervals one specific event was chosen by the interval co-ordinator. With one exception, there is no information as to the specific events within the special intervals which were chosen. Full details can be obtained from the discussion Chairman Prof. T. Saito, Geophysics Institute, Tokoku University, Sendai, Japan.

<u>Period</u>	<u>Interval Co-ordinator</u>	<u>Address</u>
13-14 July 1977	W. J. Hughes	Astronomy Dept. Boston University Boston, MA 02215, USA
16-19 Aug. 1977	J. Vero	Geodetic & Geophysical Res. Institute of the MTA H-9701 Soprou, PF5, Hungary
20-23 Sept. 1977	D. Orr	Dept. of Physics, Univ. of York York YO1 5DD, England
9-10 Dec. 1977	B. Fraser	Dept. of Physics, Univ. of Newcastle, Newcastle, New South Wales, Australia
14-15 Feb. 1978	V. Troitskaya	Institute of Physics of the Earth, Moscow D-243, USSR

Two other events were mentioned as being worthy of special study:

1. The interval just after ISEE 3 launch. The ISEE 3 magnetometer was switched on 21:40 UT 12 Aug. 1978, and reached a distance of  $50 R_E$  from the earth at about 1200 UT 15 Aug. 1978. This interval would be particularly good for solar wind correlations.

2. The event of 11 December 1977, 1600-1800 UT. This event was "discovered" at a workshop at Goddard held to study the 9-10 December interval. Both H. Singer (UCLA) and T. Fritz (NOAA) found a pulsation in the magnetometer records of their respective spacecraft; ISEE 1-2 and GOES 2. Waves have subsequently been found on SMS 2 and ATS 6. This appears to be an ideal event with which to study ground/satellite correlations in details.

## Appendix B

### Geomagnetic Field Workshop Questionnaire

1. Understanding how geomagnetic variations are produced - some important unsolved problems:

- a. What information is needed to solve existing problem?
- b. How can the information be made available?
- c. How can ground based magnetometer networks contribute?
  - i. Latitude: midlatitude (AFGL Chain, etc.) - high latitude
  - ii. Orientation: North-South; East-West
  - iii. Time resolution
- d. What type of coordinated measures are desirable?  
ground-satellite  
network-network

2. How can magnetic field data be used to predict and/or monitor substorm activity, pulsations, ring currents, convection, etc?

3. Indices:

- a. What are the inadequacies of existing indices?
- b. Should new indices be devised?

4. Calibration:

- a. Can satellite measurements be used to calibrate ground based instruments?
- b. Can ground based measurements be used to calibrate satellite instruments?

5. Data dispersal: Are existing methods adequate?
6. Ground based networks in the post IMS period:
  - a. What are current plans?
  - b. What is required?

## Appendix C

### Questionnaire Responses

Written responses to the questionnaire (Appendix B), distributed for discussion during the workshops, were submitted post factum by Major V. Patterson, Prof. R. McPherron, and Dr. Eugene W. Greenstadt, and are given below.

A. Response of Robert L. McPherron, Professor of Space Science, Department of Earth and Space Science, UCLA, Los Angeles, California

What are some of the important unsolved problems of magnetospheric physics? These include:

1. What causes the onset of a substorm expansion phase?
2. What controls where the substorm will occur, how big it will be, how long it will last?
3. What determines the properties of particles energized and injected by the substorm?
4. What are the mechanisms for redistributing injected particles?
5. What are the loss mechanisms for these particles?
6. How is the energy released by the substorm dissipated in the ionosphere?
7. What effects does this energy deposition have on the ionosphere?

Many of us working on the subject of substorms have speculative answers to most of these questions, but based on inadequate data. These models are quite controversial and are certainly far from being quantitative.

What information is needed to solve these problems?

1. Better monitoring instruments with higher time and space resolution.
2. Better distribution of instruments such as ground networks and multiple satellites.
3. Better data acquisition techniques.
4. Better archiving and retrieval systems.
5. More support of researchers studying these problems.

As a specific example, I believe great progress could be made on the question of substorm onset mechanisms if we had an auroral imaging device producing high resolution pictures of the aurora at a rate of 1 per minute. Using solar wind, with magnetospheric and ground network data obtained simultaneously, the auroral pictures would help immensely in deciding which models to use in interpreting our ground data.

What contributions can the AFGL chain of magnetometers make to substorm studies? We must first ask in what ways is the chain unique. These include:

1. One of the few constant magnetic latitude chains in the world.
2. Identical instrumentation at all stations.
3. Instruments have high sensitivity and low noise.
4. Data is acquired at very high time resolution.
5. Exceedingly accurate relative timing at all stations.
6. Data are acquired and stored in real time.
7. There is an extensive historical data file.

Geomagnetic phenomena which can be studied with the network data are those which produce strong magnetic perturbations at sub-auroral latitudes. These include substorm field aligned currents and pulsation phenomena associated with the plasmopause such as Pi2 pulsations.

Both of these subjects are currently of great interest to magnetospheric physicists and appear to be closely related topics. The onset of the expansion phase of a magnetospheric substorm is characterized by a number of events including a short burst of Pi2 pulsations and the formation of a wedge of field aligned current diverting a portion of the near earth tail current through the auroral oval. There is some evidence that the Pi2 burst is the initial transient associated with the resonant properties of the circuit carrying this field aligned current.

Since the cause of the substorm expansion onset is not presently known, it is important to identify the processes which occur near the region of onset, at the time of onset. Pi2 pulsations can be used in such studies because they define expansion onset times precisely. The AFGL network with its high sensitivity, low noise, high time resolution, accurate time, and location just equatorward of the plasmopause is ideally suited for observations of Pi2 pulsations. One important application of the network data would be to create a list of substorm expansion onsets for use in substorm research projects.

It is equally important to know where an onset occurs and how it subsequently develops. Information regarding this question can be obtained from the east-west magnetic variations (D component) measured along a constant magnetic latitude chain. The center of the sheet of field aligned current entering the ionosphere in the morning sector is near the longitude of maximum negative deviation in D. The center of the outward current is near the longitude of maximum positive deviation in D. The center of the current system is where the D perturbation is zero. The AFGL network is ideally located for determining such parameters when North America passes through the midnight sector.

The preceding comments partially answer one of the major questions, how can magnetic field data be used to monitor magnetic activity? pulsations ? etc. (Question 2 in Appendix B).

The preceding comments are also relevant to question 3 regarding possible new indices. Since the AFGL network is of limited extent in local time, it is not possible to generate planetary indices. However, the data can be used to generate indices during fixed intervals of universal time. For example, an important contribution the network data could make would be to produce pulsation indices for various types of magnetospheric wave activity. Specifically, a Pi2 index of substorm activity could be generated by band pass filtering out the 60-second period band. An indirect monitor of solar wind characteristics could be generated by band pass filtering the Pc3 band.

The final question I would like to touch on is that of data dispersal (question 5 in Appendix B). It is here that the AFGL seems to be having the most difficulty. Until very recently, few persons outside AFGL had ever seen the data. While it is possible to acquire small amounts of data in graphical form, a request to study a major portion of the digital data would not be easy to satisfy.

The cheapest and easiest way for AFGL to disperse the data would be to duplicate the entire data file as it is and send it to the World Data Center in Boulder. Alternatively, AFGL can act as a data center, filling requests as they come in; however, this requires staff specifically dedicated to this function. Still another alternative would be to provide a dial-up computer link so outside users could gain access to the on-line data files. This method is limited by the amount of data kept on line, by the data transmission rate, and by the costs of the dial-up link. It would also require software development to make possible access by other computers.

Any of the above methods is unlikely to result in extensive use of the data file because of the costs involved in using the data. To obtain such use, AFGL will have to support the cost of research on the data base. Possible methods include:

1. Reassignment of current AFGL staff.
2. Addition of new AFGL research staff.



3. Visiting scientist positions.
4. Summer research positions.
5. Consulting arrangements.
6. Grants to universities or research organizations.

If the data are to be analyzed at AFGL, additional support must be put into the mini-computer facility in the form of dedicated programmers and additional hardware and software. Without this, AFGL's staff or visitors will not be able to gain access to the data. In addition, institutional arrangements must be made whereby those interested in the data can influence program development. For example, in my opinion, a major problem with the existing data processing scheme is that suitable averages and indices are not generated by the data acquisition and archiving program at the time the data are acquired.

An attractive alternative is for the AFGL to sponsor research and development grants in outside organizations. For example, the algorithms, programs, etc. required to analyze AFGL data elsewhere could be implemented at AFGL by existing staff members provided proper documentation of these was generated by the grantees.

It seems likely that current research areas in geomagnetism will eventually become matters of continuous importance to both military and civilian agencies. When this happens, continual monitoring of magnetic activity with magnetometer networks like AFGL, and also real time processing and display of data from these networks, will be essential. I believe one important goal of AFGL research activities should be to incorporate various research tools into the real time data acquisition system so that their value in monitoring can be demonstrated.

B. Response of Dr. Eugene W. Greenstadt, Space Science Department,  
TRW Defense and Space Systems Group, Redondo Beach, California

My answers to the items on your list of questions follow. Each reply is cast in the frame of my own project rather than in the full generality of the questions, which I presume are best answered in total by a panel or a composite of such individual responses. Answers to the questionnaire:

1. a. Two types, more precisely, two scales of information are needed. First, relatively brief, say, 2-hour to 2-day intervals of data corresponding to identified events or sequences of events are needed for the study of the physical transmission of waves through the magnetosphere to the ground. Second, relatively lengthy intervals, say several hours of data each day for several months, are needed to develop and test pulsation-based indices of magnetospheric and solar wind parameters. Within either scale, the information content consists of the time and amplitude, or power, of signals in selected frequency bands.

1.b. The information can be made available from fluxgate or induction coil recordings as plots, films, tapes (or listings), depending on the application. Plots and tapes can be made available by mail; taped data can also be made available by telephone line between computers.

1.c.i. Midlatitude networks, that is, stations equatorward of the plasmapause like AFGL's, are advantageously situated to escape some of the extremes in variability of pulsation characteristics that affect stations connected to the plasmatrough. The most outstanding example is periodicity: a station at, say  $60^\circ$  magnetic latitude may pick up a resonant response in the low end of the Pc3 band, at a Pc3 amplitude, one day and the low end of the Pc5 band, at a Pc5 amplitude, the next day because of changes in density in the plasmatrough. How can such measurements be compared? Badly.

To first order, the plasmasphere above the AFGL chain tends to be more stable than the trough further north so that the stations ought to pick up signals or resonances, if any, concentrated in the Pc4 band. That should help, because the amplitude in the one band, from day to day, may be more directly relatable to differences in the level of input perturbation, or signal, at the magnetopause, and less to local variations in the magnetosphere. We do not belittle the prospect of getting one variable out of the way in this business. Further, if this approach works, it may become possible to calibrate some of the more refractory, high-latitude data so as to make them more usable.

1.c.ii. Additional reduction in variability can be achieved at certain local times, so an E-W chain increases the probability that some station will be in the optimal location often enough to build up an acceptable population of cases. This probability becomes even higher if Eskdalemuir (U.K.), for example, is considered as an eastern extension of the AFGL network.

1.c.iii. For the explicit purposes I am enunciating a sampling interval of 20 seconds and a processing interval of 5 to 10 minutes to obtain, for example, maximal amplitudes or spectral estimates, which would be adequate. This is relatively undemanding and is well within the resolution of the AFGL system.

1.d. Ground-satellite co-ordinated measurements are necessary both for studying cases and for statistical analysis. If the AFGL chain yields a decent result, then network-to-network co-ordination, particularly between the AFGL and other stations at about  $70^\circ$  would be desirable.

2. Pulsations can be monitored by visual inspection of filtered or unfiltered plots, by representations of filtered signals in terms of amplitude levels, power spectral densities, or dynamic spectra (in order of increasing cost, complexity, and information content). Such representations can be displayed as plots or recorded on tape for further processing and analysis. Some types of pulsations, P12 for example, may be predictive of substorms or even, we may speculate, of

geosynchronous satellite anomalies. Predictions of this sort are in their infancy and require investigation and development.

3.a. As far as pulsations are concerned, the inadequacy of existing indices lies in the current lack of such indices. Years ago, Saito devised a pulsation index he called Kc3, based on Pc3 measurements at one observatory, which correlated well with solar wind velocity. This development was never followed up and never expanded into a worldwide index. The IMS network offers an opportunity and, I believe, an obligation to attempt such a project.

3.b. New indices should be devised, but it will not be an easy task. It must begin as simply as possible with improved correlations that will lead to selection or establishment of stations most suitable for a worldwide monitor system. It is quite possible that the Air Force chain will serve as the core bases for recording data that can be fashioned into a worldwide index, or at least a midlatitude index.

4.a.b. For the particular investigation and application I have in mind, satellite-ground calibration, and the reverse, are intrinsic elements.

5. Yes and No. Existing methods are adequate, but the AFGL system does not appear at present to be set up to use them. First-order processing, that is, spectral selection of data has not yet been developed for either internal or external use, and phone-line call-up capability has not been established for external use. There did not appear to be a research plan at AFGL, whose unfolding would automatically result in the above facilities. For further detail, see commentary below.

6.a. Current ground-based plans seem to be mixed. Some recordings have already been terminated; some will be discontinued at the end of the IMS; some after MAGSAT; some as budgets dictate. Some stations are just now designing improvements for the future; signifying an intention to continue recording indefinitely.

6.b. What is required is largely unknown for the simple reasons that there is a sizeable phase lag between recording and analysis of IMS data. Serious inadequacies of IMS data collection, if they exist, may not become evident for a year or two. One of the major accomplishments of the IMS, in which the AFGL chain shares, is a great improvement in acquisition and recording technique, which now is ahead of the capacity of the analysis community to absorb the data. Although several significant results have already come out of the IMS, the bulk of advances in both quantity and quality will undoubtedly arise in the early 1980's.

My view is that recordings should continue toward solar maximum until analysis shows which deletions or changes will be profitable. Consider the Air Force chain and pulsations as an example: recent work has shown the global nature of some selected pulsation events; that is, several stations, both meridionally spaced and conjugate to each other, observed similar manifestations at the

same time. Some of the data were displayed during the workshop. The distance limits on such similarity have not been established. It may (it may not) be that the seven AFGL stations could be replaced by four with no serious loss of information content, but I do not think we will know until well after the IMS is over (see below).

#### Commentary

AFGL has installed an advanced system of geomagnetic data collection in which the acquisition points are advantageously located for at least some important geomagnetic investigations. Further, the data gathering and storage scheme creates a file of data of superior organization and accessibility. The file so created contains gargantuan amounts of information which can be extracted only by advanced techniques of data processing. Fortunately such techniques are available today, and at far less expense than they were even a very few years ago.

I found that certain kinds of processing had not been planned as an integral part of the AFGL facility from the outset. One purpose of the system is to record and apply field oscillations, but the basic content of the recordings from which any analysis begins is a summary of what oscillations are present at a given time. Even if the spectral content is not stored separately, and I think it definitely should be, the capacity to comb any given set of tapes for spectral content should be a routine library function fundamental to virtually any exploitation of the pulsation records, whether internally or externally originated.

In a sense, the entire AFGL net may be regarded as a single geomagnetic instrument whose application requires an associated calibration. I offer two illustrations: suppose someone is interested in studying a selected storm or sub-storm or a set of them — some IMS intervals, say. The disturbance fields would be obtained by subtracting  $S_q$ . But what is  $S_q$  for each of the AFGL observatories? Any individual wishing to examine a particular interval can hardly be expected to make a bulk analysis of the entire library to find  $S_q$  before he can begin work on a 2-day storm. A set of  $S_q$  curves or tables should be regarded as a calibration that's part of the system description. Similarly, there is a diurnal variation in baseline pulsation level that can be used to indicate the best hours for selecting passband data and the level above which pulsation events can be said to have occurred. Curves and tables of such variations should be part of the system description.

### Recommendations

I recommend an investment in data conditioning, processing, description and communications as follows:

1. Library routines, or microprocessor hardware, for digital filtering of the data with selectable passbands, start, and stop times, should be developed and debugged, or bought, with the utmost dispatch.
2. A capability of recording filtered output on tape, printed listings, and plotted graphs should be acquired. I really see no reason AFGL should not be accumulating, storing, and perhaps even mailing out, the same sort of *f-t* diagrams that Onagawa and Kakioka are providing.
3. Average, quiet-time characteristics of each station at all accessible frequencies should be discovered, recorded, listed, and printed as part of the system description.
4. A capability of telephone line coupling that would permit external computer access to any stored data set should be established.

In summary, the Air Force magnetometer net can be a productive element in geomagnetic research and application, but some definite steps need to be made now to turn promise into reality.

### C. Response of Major Vern Patterson, USAF, Air Weather Service, Global Weather Central, Offutt AFB, Nebraska

1.a. What information is needed to solve existing problems? I believe a means needs to be developed to provide worldwide or hemispherical maps of geomagnetic variations. These maps should include spatial and temporal changes. (One possibility would be to produce a film of a computer mapping program.) Although the need exists to include satellite data, insufficient data is available at this time. However, maps should be made using all available ground-based magnetometer data. One of the World Data Centers would be an ideal location for such an effort. I am firmly convinced that the present magnetometer data is underutilized because of difficulty in handling it and in its use as either a point or line source. A means of displaying the data would have to be worked out and this would probably be a good topic for a future workshop and/or for a suggested funding program for research or studies on the possible applications of existing data.

1.b. How can the information be made available? Data in a standard format should be provided to a World Data Center for distribution. Common formats are a key element whether or not the data is provided by the World Data Center.

1.c. How can ground-based magnetometer networks contribute?

- i. Latitude: Midlatitude, high-latitude, both are required. Probably finer resolution is required at the higher latitudes.
- ii. Orientation: North-South; East-West; both are required.

iii. Time-resolution: Depends on the ability to time synchronize the sites providing the data for the world maps. I would like to see the time resolution set at 1 minute. This might be impossible for a large number of sites and one might have to go to 5-minute resolution. The resolution should not be longer than 5 minutes.

1.d. What type of coordinated measurements are desirable? I believe that most emphasis should be placed on network-to-network co-ordination at this time.

2. How can magnetic field data be used to predict? This topic is best answered by the scientific community. This might be a good topic for a mini-workshop, a review article, or for a notice application program.

3. Indices. I firmly believe that present indices are inadequate and that they are being greatly misused. I am not sure that they can be improved greatly but a review article explaining their origin, what they measure, and deficiencies is needed.

4. Calibration. This question should be answered by Bob McPherron, UCLA.

5. Data dispersal: Are existing methods adequate? No! Data sources are not well known or centralized. Data formats are not consistent.

6. Ground-based networks in the post IMS period?

a. What are current plans? Check with Dr. J. Joselyn, SEL/NOAA.

b. What is required? It was agreed that strong support should be given to maintaining the IMS Network.

#### D. Other

##### The AFGL Magnetometer Network:

It was agreed:

1. AFGL should develop a time-series data base management system to provide data to various researchers. However, it is recognized that this must be a limited effort as AFGL is not a data center.

2. In the future AFGL should consider possible extension of their present system to include part of Dr. Stuart's chain in Western Europe. He has located several stations along the 55° N latitude line used by AFGL.

3. AFGL and USCGS (U.S. Coast and Geodetic Survey) should look into the possible combined use of stations.

##### All Magnetometer Networks:

1. The present magnetometer networks provide the best set of magnetometer data ever available. However, because of the research lag in using the data these networks are all facing financial reductions before their full scientific importance is realized.

2. A great deal of concern was expressed about the potential loss of the IMS (International Magnetospheric Study) Network and the reduction or loss of other networks. It appears that the IMS Network was justified on its ability to provide near-real time science rather than on its being the most efficient way to collect and store data. Now since very little real-time science has been accomplished some NOAA personnel see little use in continuing the network upon completion of the program.

3. It was generally agreed upon that a letter should be prepared on behalf of the workshop providing strong support to maintain the IMS Network.

#### Applications:

##### 1. General

a. It was suggested that a second workshop should be held within six to twelve months. This group should be smaller and should study a particular event or selected problem. This group would take a tiger-team approach.

b. Increased emphasis needs to be placed on data analysis rather than just data collection.

c. Increased co-ordination between the solid earth and space physics workers will improve geomagnetic field research. Although each group is concerned with different portions of the data spectrum (solid earth - internal geomagnetic field; space physics - external geomagnetic field), each group must be aware of developments over the full spectrum.

d. It was suggested that a small amount of money be provided to support a selective notice application funding program. An announcement of opportunity could be made in which scientists would be invited to submit proposals to analyze available data.

e. The present geomagnetic networks should not be reduced as these data will provide excellent correlative support to upcoming satellite systems.

f. It was suggested that a review article be prepared covering all the known magnetic indices. This article would describe the indices, what they measure, and the deficiencies.

##### 2. Potential Application of AFGI Network.

a. Improved reliability of AWS real time sites.

b. Use of pulsation data to specify the occurrence and location of substorms and to specify solar wind velocities.

c. Correlative use of magnetometer data along with the SSJ/3 data to determine the Q index.

ATTENDEES AT THE WORKSHOP ON GEOMAGNETISM  
Air Force Geophysics Laboratory

April 6-7, 1979

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